A STUDY OF DAM FAILURES

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Chuan Tze Hsiung

1949

This is to certify that the

thesis entitled

A STUDY OF DAM FAILURES

presented by

Chuan Tze Hsiung

has been accepted towards fulfillment
of the requirements for

M.S. degree in C.E.

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Date May 27, 1949

A STUDY OF DAM FAILURES

By

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A THESIS

Submitted to the Graduate School of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

Department of Civil Engineering

1949

ACKNOWLEDGEMENT

The writer wishes to express his appreciation to Prof. Claude M. Cade whose helpful suggestion and guidance made this thesis possible.

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I. INTRODUCTION

It is of prime importance for engineers charged with the design and construction of dams to study the failures of the past. Valuable information can be obtained from a careful study of the design of dams that have failed and the causes and nature of the failure. The worst disaster in history resulting from failure of manmade structures was the failure of the Johnstown Dam. This disaster caused the engineers to pay much more attention to the core wall and the seepage through and around the dam. The failure of the St. Frances Dam produced many works about investigating the dam foundation. The lesson from the failure of the Lower Otay Dam taught us that the earth and rock fill dams must be protected from overflow. The sliding of the Summer Lake Dam indicated the movement of foundation. Cracking occurred on the concrete faces rendering improvement of the quality of the concrete and special cement for the use of dam-building necessary. It is not overstated that a great part of the development of dam design and construction can be attributed to the investigation of dam failures.

The purpose of this thesis is to investigate the causes of dam failures. The writer is going to find out where engineers have to put much more of their attention to designing and constructing a dam. The paper contains also a tabulated summary of 349 dams that have wholly or partly failed and a classification of causes of their failures. And also a brief history of dams will be given first, in order to give a general idea about the development of the theories and construction methods.

II. PURPOSES AND TYPES OF DAMS

A dam is a barrier built across a stream or across a valley or other depression, to raise the level of the water surface, to retain or store water for domestic water supply, for the regulation of stream flow, for the improvement of navigation and the generation of hydroelectic power. Programs were also under way for conservation of migratory of fish in rivers where dams made it impossible for fish to go upstream to spawn.

The principal types of dams are: (a). earth dams, (b). solid masonry or concrete gravity dams, (c). rock-fill dams, (d). arch dams, (e). timber dams, and (f). steel dams. A brief history of development of dams will be given in the next chapter.

III. BRIEF HISTORY OF DAMS

(1) Earth dams

Earth and masonry dams are two oldest types of dams which were recorded in the human history. Probably the first dams were composed of earth. The dam built by Marduk is believed to be one of the earliest, many years before Abraham the founder of the Jewish race. About 4,200 years ago, China built dikes and dams for the purpose of flood control and river regulation[1]. The common characteristic of all the ancient dams is their large size. The Panda's Tank built in the fourth century B. C. lasted till 1810, was formed by an earth embankment 8,400 ft. long and 22 ft. high. The Kala Tank, probably built early in the first century, had an embankment 6 miles long and 60 ft. high. India built a great number of earth dams in her ancient time. There were more than 50,000 in Madras Presidency and 37,000 in the Mysore district. At least one of them dated back to eighth or ninth century[2]. The Mudduck Masur Tank[3] built over 400 years ago, had a capacity of about 284 billion gallons. However, theory had been

1). Matschoss, Great Engineers, 1939, P. 5.
2). E. W. Lane, "Dams-Ancient & Modern," J. Assoc. Chinese & American Eng. Vol. XIX, No. 6, Nov-Dec, 1938.
3). Wagman, Desing & Construction of Dams, 1911, P. 233.

little used at that time in the design of earth dams. The successful designer has been governed by the lessons gained through experiences. The major features in design and construction of earth dams consist of spillway, seepage, influence of earthquake, core wall and cutoff wall, etc.

The design of spillway is one of the most important works on earth dams. As masonry dams with an insufficient spillway generally stand overtopping to a considerable depth without serious damage, but with an earth dam, overtopping usually means failure. Some special types of spillways have been developed and become of common use, such as chute spillways[4)], side channel spillways[5)], and shaft spillways[6)].

The Francis' formula is generally used to determine the capacity discharge of spillway[7)]. The modified form of this formula can meet the conditions of end contraction weirs[8)]. From a study of the data contained in the published experiments of discharge capacity of the Wilson and Keokuk Dams, the approximate

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4). A. L. Alin, Report on Chute Spillway, U. S. Eng. Off., Dension, Tex., Dec. 1939.

5). "Side Channel Spillway," Trans., A.S.C.E., Vol. 89, 1926, P. 881.

6). "Tests of Circular Weirs," Civil Eng., Apr. 1939, P. 247.

7). U. S. Geol. Survey Water Supply Paper 200.

8). Creager-Justin-Hinds, Eng. for Dams, 1947, Vol. II. P, 365.

values of the coefficient of contraction in the modified Francis' equation was derived[9].

For investigating the percolation around or under the dams, different theories and methods were developed. Bligh's Theory based on the assumption[10] that the water follows a path along the contact of the dam, (including the cutoff walls) with the foundation material. A equation was derived to determine the minimum safe length of the creep line. In 1911, a paper appeared, by Arnold G. Koening[11], giving rules for the design of masonry dams on earth foundation which contains a number of valuable ideas. In 1934, Mr. Lane published his paper "Security from Under-seepage Masonry Dams on Earth Foundations,"[12] recommending that the line of flow will follow the line of creep, but the vertical contact is considered more effective than the horizontal contact and that the creep ratio should be changed. For analyzing the line of seepage and uplift, two methods can be used, namely, flow-net[13], electrical method[14]. Danger from uplift was recongnized and was considered as early as 1882, in the design of

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9). W. G. Bligh, Practical Design of Irrigation Work, 1907.
10). "Dams, Banages and Weirs on Porous Foundation," Egn. News, Dec 29, 1910.
11). Trans., A.S.C.E., 1935, P. 1235.
12). Trans., A.S.C.E., 1911, P. 175.

the Vyrnwy Dam of the Liverpool (England) Water System. The first American dam in the design of which allowance was made for uplift is the Wachusetts Dam in Mass. (1900-06) without drainage system. The Olive Bridge Dam, in New York State (1908-14) had drains in the masonry, but lacked foundation drainge. Large dams in the United States, first provided with foundation and masonry drains to reduce uplift are believed to be the Medina Dam, in Texas (1911-12) and the Arrowrock and Elephant Butts Dams, in Idaho and New Mexico, respectively[15)].

The original and mathematical theory[16)] of the flow net rests upon the foundation of differential calculus. Later Laplace, Gauss, Stokes, William Thompson, Maxwell and a host of other mathematicians and physicists enriched our knowledge of the theory and its application. The flow net was used by Hinderks for the investigation in pressure distribution in siphon spillways (1928) and then employed at Hanover from the problem of flow under roller dams. This method was introduced in the United States by Freeman in 1929.

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13). John R. Freeman, Hydraulic Labaratory Practice, 1929, P. 605.
14). "Uplift and Seepage under Dams on Sand," Trans., A.S.C.E., 1935, P. 1363.
15). Trans., A.S.C.E., 1934, P. 1042.
16). Civil Eng. Vol. 4, No. 10, 1934, P. 510.

As far as could be discovered, the first application of the electrical analogy to the solution of hydraulic problems to be published was by N. N. Pavlovski.

For preventing the seepage of water around or under the dam, the core wall and cutoff wall are built. The core wall ofpuddle was first used before concrete became common. The Druids Lake Dam, Md. (1871); Swansea Dam in South Wales, Great Britain (1879); Dam in Ashti, India (1883); Dam in Johnstown, Penn. (1889); and Yarrow, England (1905) were the earlier dams built with puddle core. From then on, the core walls made of masonry, concrete, reinforced concrete, have been usually constructed for earth dams.

For the design of earth dams, there are still more following notable research works:

1. J. B. T. Colman[17)] gave interesting data on the pressures of water, under various conditions under a model dam with a pervious foundation.

2. In 1901, a board of consulting engineers made a series of tests of the dams of the Croton Water Shed and located the lines of saturation in structures.

3. James B. Hays gave some interesting and thorough investigations on the seepage and loss of head

17). "The Action of Water under Dams," Trans., A.S.C.E., 1916, P. 421.

for certain materials[18].

4. D. C. Henry described seepage experiments showing reduction in seepage due to the inclusion of vegetable matter in the soil[19].

5. Allen Hazen determined the coefficient of friction of various materials[20], [21], and F. W. Scheifenhelm gave tests made to determine such coefficients.

The elastic theory has been used for determining the stress in foundations. In 1934, Juergenson[22] derived a very simple formula for obtaining the approximate shear stress in a plastic layer in the foundation of an earth dam of triangular cross-section. K. E. Petterson first applied the circle method to analysis of a soil failure in 1916[23]. Due to the later developments made by W. Fellenius, Terzaghi, Gilbou, Taylor[24] and others, became a satisfactory analysis known as dangerous circle method of the stability of slopes, embankments, and foundations[25].

The practical criteria for the design of earth

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18). "Designing an Earth Dam Having a Gravel Foundation with the Result Obtained in Tests on a Model," Trans., A.S.C.E., 1917, P. 1.
19). Eng. News, Vol. 57, P. 251.
20). Trans., A.S.C.E., 1919-20, P. 1728.
21). Trans., A.S.C.E., 1917, P. 907.
22). Leo Juergenson in J. Boston Soc. C. E. July 1934.
23). Creager-Justin-Hinds, 1947, Vol. 3, Cap. 18.
24). Donald W. Taylor, "Stability of Earth Slopes," J. Boston Soc. Eng., Vol. 24, July, 1937, P. 197.
25). Creager-Justin-Hinds, L947, Vol. 3, P. 662.

dams may be stated briefly as follows: An earth dam should be designed so that:[25), 26)]

1. There is no danger of overtopping (i.e. sufficient spillway capacity and sufficient freeboard).

2. The seepage line is well within the downstream face.

3. The upstream face slope is safe against sudden drawdown.

4. The upstream and downstream slope is flat enough that, with the materials utilized in the embankment they will be stable and show a satisfactory factor of safety by recongnized methods of analysis.

5. The upstream and downstream slopes of the earth dam are flat enough that the shear stress induced in the foundation is enough less than the shear strength of the material in the foundation to insure a suitable factor of safety.

6. There is no opportunity for the free passage of water from the upstream to the downstream face.

7. Water which passes through and under the dam when it reaches the discharge surface has a pressure and velosity so small that it is incapable of moving the material of which the dam or its foundation is com-

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26). "The Design of Earth Dams," Trans., A.S.C.E., 1924, P. 1.

posed.

8. The upstream face is properly protected against wave action and the downstream face is protected against the action of rain.

The hydraulic fill dam is a modified type of earth dam, the materials of which are transported onto dam in the construction and distributed to their final position in the dam by water[27]. This method was first introduced as known as hydraulic mining and was used in making small dams in California. The first dam built partly by this method was the Temscal Dam in 1866 at Oakland, California[28]. The dam first really built with hydraulic process was probably the dam at Tyler, Texas completed in 1894[28]. In 1895, the La Mesa Dam was constructed in Calif. to store flood-water[29]. Since then, a great number of hydraulic fill dams were constructed. The largest earth dam so far built in full by the hydraulic fill method is the Fort Peck Dam of 242 ft. height.

James D. Schuyler published a paper[30] about the theory on the hydraulic fill dam construction with the following conclusions:

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27). Trans., A.S.C.E., 1922, P. 1181.
28). "Earth Dam," Eng. News, 1902, P. 187.
29), 30). "Recent Practice in Hydraulic Fill Dam Construction," Trans., A.S.C.E., 1907.

1. The inner third of the dam should be composed of material which should consòlidate into a mass impervious to water.

2. The outer half of each of the other thirds of the dam should consist of coarse porous material, permitting the passage of water.

3. The inner halves of the outer thirds of the dam should be a mixture of coarse and fine material, which should act as a filter to retain the fine particles of the inner third while allowing water to percolate slowly.

In 1920, Allen Hazen[31)] emphasised the importance of core materials, borings and increasing the size of toes. The following results were obtained:

1. It is not well to build an hydraulic fill dam of material of which any large percentage consists of clay or of particles less than 0.01 mm in diameter.

2. By reducing the construction pool to a minimum and by constrolling it and the quanlities of water used for sluicing, the core material may be held to a certain degree of coarseness by wasting all smaller particles. An effective size of 0.01 mm may reasonably be sought.

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31). "Recent Practice in Hydraulic-fill Dam Construction," Trans., A.S.C.E., 1907.

3. To study by borings the actural consolidation of the material, and to adjust the construction of upper parts of the dam to the demonstrated condition of that which lies below.

4. To make the toes large enough to resist with an ample factor of safety the whole pressure of the core material as a liquid until there is demonstrated of the solidation of the core to a point where horizontal pressure is eliminated.

5. To increase the weight and solidity of toe by the use of rock fill, placed hydraulically or otherwise.

6. Stability is increased by compactness.

Gilboy presents a formula[32)] for the stability of hydraulic fill dams, with which the factor of safety may be calculated.

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32). Glennon Gilboy, "Mechanics of Hydraulic-fill Dam," J. Boston Soc. C. E., Vol. 20, No. 3, July, 1934.

(2) Masonry Dams

The masonry dam is another of lod type of dams recorded in our history. The most ancient masonry dam of which there is recorded was built in Egypt over 4000 B. C. about twelve miles south of Memphis[33]. It was about 1500 ft. long and 50 ft. high. The largest ancient masonry dam was built in Arabia about 1700 B. C. for irrigation and water supply and collapsed in the third century A. D. It is said to have been a mi. long, 120 ft. high and 500 ft. thick at the base. The first ones in what might be considered our modern era of dam-buildings were in the arid regions of Spain. The most ancient of the dams seems to be the Elche Dam, built by the Moors in 913. An ancient dike of China was built in 15th century. It is about 30 ft. high over 100 ft. wide on the top and 35 mi. long[34]. The Almanza Dam built in Albacete Province, Spain, was in service prior to 1568. This is believed to be the first dam built of gravity type[35]. The first modern gravity dam constructed in the United States probably was the Old Croton Dam, New York, 1837-42.

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33). Eng. News-Rec., Oct. 6, 1921, P. 556.

34). E. W. Lane, "Dams-Ancient & Modern," J. Assoc. Chinese & American Eng. Vol. XIX, No. 6, Nov.-Dec, 1938.

35). Wagman, Design & Construction of Dams, 1911, P. 1.

The dams built in Spain during the Middle Ages were subject to excessive stresses due to dead weight alone. Modern design dates from about 1853, when a French engineer, de Sazilly, deduced the first general equations for the profiles of dams; his designs were on the two conditions:

1. The pressures sustained by the masonry or its foundation must never exceed a certain safe limit; and

2. There must be no possibility of any portion of the masonry sliding on the below or of the whole wall moving on the foundation.

Frence engineer, M. Delocre was the next one who investigated further the design of Furens Dam. In one of his works published in 1866, he states that the additional strangth might be obtained by building a dam on a horizontal curve in plan.

Avout 1881, Prof. W. J. M. Rankine, an English engineer, introduced an important idea. He evolved a theoretical profile that would meet the required pressures economically limiting the lines of pressures to the middle third of the section. Also he pointed out two principles for masonry dams:

1. The limit for the intensity of vertical pressure is lower at the outer face than at the inner.

2. No tension must be allowed in the masonry.

In 1875, M. Bouvier proposed to calculate the pressure of the whole resultant pressure at any joint by considering the joint to be projected at right angles to the line of action of the resultant.

Molesworth offered an empirical formular in 1886 for determining the profile of a masonry dam.

M. Guillemain advocated a new method of determining profiles of masonry dams, based upon the consideration of oblique joints.

From then on, many tests on models of dams were made from 1900 to 1904 by L. W. Atcherley, Sir John W. Ottley, and by John S. Wilson. They reached these conclusions:

1. Tensile stresses, which may have large local magnitude, occur at the upstream toe,

2. Tensile stresses occur in no other parts of the dam,

3. The stresses on the foundation are distributed almostly uniformly,

4. For joints above the foundation, the usual assumption of the linear distribution of normal stress on horizontal lpanes is approximately correct, and overestimates somewhat the maximum intensity of stress,

5. The maximum compressive stresses on the downstream face occur on planes normal to the face, and

6. Near the base of the dam, the maximum com-

pressive stresses on horizontal planes do not exceed those calculated on the assumption of linear distribution of normal stress.

Modern dam design may be said to date from the Quaker Bridge dam of the New York Water Supply. It was completed in 1907. There was no uplift being considered for masonry dam until 1912[36]. Before then, according to the earlier group of theories--which comprised Maurice Levy's Law, 1895; the Lieckfeldt Method, 1898; the Link Theory, 1910; and others (as Pelletran, 1897)--the uplift was assumed to penetrate into the material through cracks and the horizontal or hydrostatic pressure of water was assumed to be exerted externally on the face of the dam[37]. In 1912, Charles L. Harrison proposed[38] three possible general conditions:

1. Contact with a rock bed such as would preclude uplift, and no joints in the masonry.

2. Porosity such that the water pressure would be at the full reservoir head, at the heel and the tailrace head at the toe, varying uniformly for intermediate points.

3. Full hydrostatic head at the heel and the head

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36). "Water-proof Masonry Dam," Trans., A.S.C.E., 1927, P. 236.

37). "Uplift Pressure," Proc., A.S.C.E., 1945, P. 1474.

38). Trans., A.S.C.E., 1912, P. 142.

of the issuing stream at the toe.

The modern principle, accepted by Karl Terzaghi (1934), P. Fillunger (1913), and many other research workers in all parts of the world is that water filters through the natural pores of the material of the dam. The uplift force was proved to be a certain law and capable of analysis by laboratory experimentation. The average value of the "effective superficial porosity" was found to be 0.91 with a probable error equal to 0.014 and the uplift factor was recommended 85%[39)].

Until 1933, the stability of a straight gravity dam against failure by sliding was usually determined by calculating the ratio of the total horizontal force to the "sliding factor", and comparing this ratio with the friction coefficient for concrete sliding on concrete or concrete sliding on rock. Since 1933, according to D. C. Henny's method for calculating the factor of safety against downstream movement, including allowances for shearing strength[40)], engineers of the United States Bureau of Reclamation have been considering the stability of straight gravity dams on the basis of the shear-friction factor of safety[41)].

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39). "Uplift Pressure," Proc., A.S.C.E., 1945, P. 1474.

40). "Stability of Straight Concrete Gravity Dams," Trans., A.S.C.E., 1934, P. 1041.

41). "Masonry Dams," Trans., A.S.C.E., 1941, P. 1115.

One of the most important developments in masonry dam design since 1924 has been the gradual improvement in methods of analyzing stress conditions.

A. V. Karpov concluded[42)] that the safety of the structure from the viewpoint of stress conditions should be judged on the basis of a three-dimensional state rather than on the basis of the maximum direct stress in one direction, the condition which usually constituted the governing criterion in early examples of masonry dam design.

Bureau of Reclamation have used the theories on local stress concentrations to design masonry dams of both arch and gravity types[43)].

The development of the trial load method of analyzing masonry dams was begun in the Denver, Colo., Office of the United States Bureau of Reclamation in 1923[44)], about the same time a similar procedure was being investigated in Europe.

In 1925, Fredrik Vogt began to investigate the

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42). The Military Engineer, Nov.-Dec., 1938, P. 418.

43). a. "The Stress Function & Photo-elasticity Applied to Dams," Trans., A.S.C.E., 1938, P. 1240.
b. "The Stresses Around Circular Holes in Dams & Buttresses," Trans., A.S.C.E., 1938, P. 133.
c. "Stresses Around Galleries in Concrete Dams," The Eng., Oct. 7, 1938, P. 382.

44). "Trial Load Method of Analyzing Arch Dams," Bull. No. 1, Part V--Techn. Inv., Boulder Canyon Proj., Final Reports, Burea of Recl., 1938.

methods[45] of analyzing effects of foundation and abutment deformations and methods of determining the true nonlinear distribution of stress within the structure.

In order to prevent cracks for concrete dam, the T.V.A. (The Tennessee Valley Authority) adopted the following methods in the construction of Hiwassee Dam,

1. The use of low-heat cement;
2. A low cement content;
3. Thin casting lifts;
4. Long exposure periods;
5. Artificial cooling of the mixing water;
6. Washing, rinsing, and cooling of the aggregate;
7. Cleanup of horizontal joints between lifts;
8. The use of steel reinforcement;
9. Diagonal Keyways on bulkhead joints, and
10. Curing and winter protection.

None of these methods is novel or original, but the combination of all of them on one job is believed to be unique.

Houk and Keener listed 25 basic assumptions involed in the design of important masonry dams[46], and there are also six rules governing the stress condition and safety factor, which are used to design masonry dams[47].

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46). Houk and Keener, Masonry Dams, A Symposium Basic Design Assumptions, Proc., A.S.C.E., 1940, P. 813.

47). Creager-Justin-Hinds, Engineering for Dams, Vol. II, PP. 293-315, 1947.

(3) Rock-fill Dams

About 90 years ago there was developed, in Calif. and other western states, a dam of a distint type. This was the rock-fill dam, which in recent years has been built to heights such 270-ft. Dix., Kentucky (1915-1925); 328-ft. at Salt Springs, California (1931); and 425 ft. at Mud Mountain, Wash. (under construction --Jan. 1947).

They are generally built in relatively remote location where the engineer uses the material at hand for his structure. Foundation conditions are often a determining element in selecting a rock fill dam as the best type to be built. Rock fill dams are composed of three elements: A loose rock fill forming the mass of the dam; an impervious face next to the water, and a rubble cushion between the two.

The design and construction of rock fill dams originated in Calif. soon after the discovery of gold in 1848. French Lake Dam, 64 ft. high and completed in 1859, is believed to be the first true rock fill dam ever constructed[48)]. The Bowman Dam on Canyon Creek was built in 1872, as a log. crib dam about 70 ft.

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48). Davis, Handbook of Applied Hydraulics, 1942, P. 289.

high. In 1876, the dam was raised to a height of 100 ft. This dam in its major part represented the modern plan of rock fill dams. The dry rubble wall on the downstream face, which retained the interior fill, may have been built as a measure of economy owing to the cost of blasting the rock.

The First Fordyce Dam was built of dry rubble with timber facing in 1873. This dam was placed in front of the old dam, a concrete outoff wall built in the end concrete face. These foregoing mentioned 3 dams represent a change from the old log crib type to one in which the rock fill alone resisted the forces of water.

The first dam of the best rock fill type was the Escondida Dam, Calif., built in 1895. A loose rock fill supported an ample dry rubble wall which was faced with timber.

Bear River and Meadow Lake Dams, Calif. were built in 1900-03. The Utica Dam of the Utica Mining Co., Calif., was completed in 1908[49]. Those three dams are the last rock fill dams to have the downstream face protected by a dry rubble wall.

The first time the reinforced concrete facing was used in the rock fill type was in 1910. This was

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49). Trans., A.S.C.E., 1939, P. 23.

Refief Dam,Calif., about 140 ft. high.

The small dam at Chatswork Park, in South Calif., built in 1896, was probably the first dam in which concrete was used as a facing. The Skagway Dam built in 1901 is believed to be the first one having steel facing.

(4) Arch Dams

There are three different theories used to analyze the stress for arch dams. The first one is called cylinder theory[50)] with which the stresses computed are only approximate because an arch slice from a dam is not a complete ring. The elastic theory is the second one developed by William Cain[51)] in 1922. It gives a better idea of actual stresses and permits allowance for temperature change, foundation yielding, earthquake forces, and irregular arch forms[52)]. The last one is the trial-load method of analyzing dams. The works of H. E. Gumer, Prof. Rohn, and Albert Stukie in Europe and that of Julian Hinds, C. H. Howell, and A. C. Jaquith in the United States have paved the way for the present method[53)]. Development of the trial load method was begun in the Denver Office of the U. S.

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50). Trans., A.S.C.E., 1915, P. 564; 1919-20, P. 2027.

Bur. of Reclamation in 1933.

The first arch dam recorded in engineering history was Poutalts Dam built in Austria in 1611[54]. The first arch dam constructed in America was Bear Valley Dam, in the San Bernardine Mountains of Southern Calif. in 1883. It was followed by the 95 ft. Sweetwater Dam, in 1888 and the 88-ft. Upper Otay Dam in 1900, both near San Diego, Calif.[55]. Lake Chusman Dam, a 236 ft. curved gravity dam constructed near Denver, Colo., in 1904, was the first high dam for which a careful attempt was made to analyze arch action. Since 1904, many arch dams have been built in the U. S. and certain foreign countries. The highest dam in the world, up to date, is the Boulder Dam, of arch gravity type, which was completed in 1936, 726 ft. high.

A number of arch dams has been investigated for the purpose of finding the safety factors of the dams. The results thereof emphasized the importance of controlling the changes in concrete temperature and also that the trial-load method of analyzing arch and can-

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51). "The Circular Arch under Normal Loads," Trans., A.S.C.E., 1932, PP. 233-283.

52). Creager-Justin-Hinds, Engineering for Dams, 1947, Vol. II, P. 500.

53). "Design of Arch Dam," Trans., A.S.C.E., 1941, P. 1131.

54). West. Constr. News, Apr. 10, 1932, PP. 451-452.

55). "The Design & Construction of Dams," by Wegman, 1927.

tilever action in curved concrete dams furnishes a satisfactory basis for the design of arch dams of any type and size[56), 57)].

(5) Buttress Dams

This is a modified type of gravity dams. The principal structural elements of buttress dams are the water-supporting upstream face, or deck, and the buttresses. An advantage claimed for the buttress dam having an upstream face with considerable batter is that it cannot overturn, as the resultant of all forces, for any depth of water, falls well within the base. Another advantage in due to its lighter weight per square foot of area covered. Therefore it can be made to exert less unit pressure on the foundation than a solid dam[58)].

The earlier buttress dam belonged to Multiple-arch type, was the Meer Allum Dam in India, built in about 1800. Its buttresses were different from the present ones, because they were built with vertical upstream faces. The Australian engineer J. D. Derry

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56). "Report on Arch Dam Investigation," Vols. I & III, the Eng. Foundation, 1927, and 1933.
57). Trans., A.S.C.E., Vol. 99, P. 897.
58). Creager-Justin-Hinds, Engineering for Dams, 1947, Vol. I, P. 45.

designed a dam in 1891, which probably was the first one somewhat similar to the present-day multiple arch dam.

The Ambursen type dam has borne the name of its inventor since 1903. More than 391 dams of this type have been built in the world up to 1942[59].

W. M. Ransom introduced a new type about 1908, called the Ransom Dam. Only two recorded examples are found, one at Columbia, N. J. and one near Cleveland, Ohio.

The Columnar buttress dam, a modification of Ambursen dam, was designed by W. S. Morton around 1910. Only one example is recorded as having been constructed about 1927 in Missouri. Similar to this type there was a built in India-China about 1912. The modified type is called truss-buttress. The difference between Columnar and truss-buttress dams is that for the later heavy vertical trusses of reinforced concrete, instead of columns, took the place of the customary solid buttresses.

Various engineers have advocated designs for buttress dams wherein the sloping upstream deck slab is constructed monolithically with the buttress and rigidly tied to it, with the deck slab cantilevered out on each side so that the construction or construction joint comes in the center of the span. Only one example of this type is recorded, constructed about 1924 in Maine.

In 1926, F. A. Noetzli designed a new type of butturess dams, called roundhead buttress dam, the upstream water-supporting member of which is provided with a radial face. The water pressure is transmitted in direct compression through the flared water-bearing member to the buttress below. The first dam of this type was the Don Martin Dam, built in 1931 by the National Irrigation Commission of Mexico[60]. The second one was built in 1936 in Switzerland. The third completed one was the Cruz del Eji Dam, in Argentina. This type of deck has several distinct advantages: 1. The entire deck is in compression under full water; 2. Little steel reinforcement is required as bending and diagonal tension stresses are theoretically eliminated; and 3. Savings in construction cost may in some instances be effected through the use of the mass concrete construction method.

When the curved upstream face of the round buttress head is substituted with a series of three planes, this new type is called diamond-head buttress dam. There has been only one structure of this type built at Haweswater, England[61].

Sometimes the multiple dome dam may be slightly more economical than the canventional multiple-arch type. An important principle has been demonstrated by

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59). Trans., A.S.C.E., 1935, P. 1303.
60). Trans., A.S.C.E., 1932, P. 835.
61). Davis, Handbook of Applied Hydraulics, P. 199.

the construction of the 250 ft. high Coolige Dam built in 1928. The principle is that the thick buttresses and wide buttress spacings, used in connection with high dams, may offer greater economy than obtainable with close buttress spacings and relatively thin masonry construction[62].

(6) Timber Dams

Timber dams were formerly much used in the United States. However, timber dams of this type are not built so often now. The large maintenance charges and leakage have created a prejudice against this type of dam. However, this type is sometimes applicable in cases of considerable first cost and in location where virgin timber is plentiful.

Timber dams can also be subdivided into six different types, namely, brushwood dams, log-dams, crib dams pile dams, plank dams, and framed timber dams.

The following dams are picked up as good examples to indicate the fact that some old timber dams still have served for many years successfully.

The dams across the Schuylkill River at Plymouth was built in 1819 on a rockbed. It stood for 39 years, with standing successfully floods that rose to a height

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62). Eng. News-Record, 1928, P. 438.

of 11 ft. above its crest. The structure was replaced in 1858 by a new construction.

The dam at New Hartford, Conn. was built in 1847 across the Farmington River. After the dam had been standing about 20 years, the upper 10 ft. had to be renewed, as the old stuff had become rotten.

The Felix dam was built in 1855 about 6 miles above Reading, Pa. It had been subjected successfully several times to heavy ice-floods.

The Columbia Dam was built in 1875 across the Susquehanna River at Columbia, Penn. It was made with a wide crest and the results have proved to be very satisfactory.

The Holyoke Dam was built in 1894 across the Connecticut River. It had been damage by the flowing of water, ice and logs. In order to protect the dam against such injuries, a large inclined apron of cribwork was built in front of the dam from 1868 to 1870. Some lessons have been taught by this old timber dam:

1. A wooden dam should not be left hollow, as the foul air on the inside will eventually rot the timber. A stone filling will not prevent the decay, but a tight filling of gravel will protect the timber against rotting.

2. A masonry shelf on a masonry abutment should not take the place of the last frame of a dam. The

dam will probably settle but the masonry will not, and thus a distortion will be produced in the framing of the dam.

3. The downstream face of the dam should never be vertical unless the height be very insignificant.

4. An apron should be provided and given a proper form to prevent the water from washing out the riverbed in front of it.

The Canyon Ferry Dam was built across the Missouri River near Helena Montana in 1894. It was founded on a bed of gravel and granite sand, which is almost impervious to water. Both above and below the crib dam a row of triple-lap sheet-piling made of 3 by 12 inch plank stiffly bolted together, was driven to a depth of about 12 ft. below the riverbed.

(7) Steel Dams

The use of structural steel for the building of dams has not been very extensive in the United States. Only three steel dams have been built. The Ash Fork Dam in Arizona is believed to be first steel dam. It was built in 1898. The steel portion of the dam, founded on rock bed a length of 184 ft., and its greatest height was 46 ft. The second one of this general type was the Rdridge Dam in Houghton County, Michigan.

Both of them have given satisfactory results. A third was built in the Missouri River near Helena, Mont. in 1905 to 1907, but failed after about one year's service. The cause of the failure was due to the fact that the center part was built on a defective foundation.

Steel dams can be divided into several types according to the ways of design. Four of these which are worthy of consideration are:

1. Deck type;
2. Arch type;
3. Multiple arch type; and
4. Multiple suspension type.

IV. FAILURES OF EARTH DAMS

Of the 349 investigated cases, there were 195 earth dams failed through 15 different causes. 69 of these failures were due to insufficient capacity of spillway; 46, due to inadequate cutoffs; 14, due to faulty construction; 6, due to faulty design; 5, due to inadequate means for stream control during construction; 10, due to excessive quantities of clay; 1, due to ice pressure; 3, due to burrowing rodents; 9, due to erosion; 2, due to earthquake; 5, due to wind action; 14, due to miscellaneous causes; and 6, due to the

failure of the bottom.

It is to be noted here that only two dams recored in the engineering history failed due to earthquake, and they were all earth dams.

The failure of each case will be given in some details in the following sections.

(1) Failure due to Insufficient Spillways

1. Lebanon Dam, Ohio--Reservoir having an area of 40 acres failed July 10, 1882. The embankment, which was 30 ft. high was destroyed by water flowing over the its crest. Five bridges and many houses were swept away--E.N. Vol. 9, P. 240; E.N. Vol. 47, P. 506.

2. South Fork Dam, Pa.--Failed on May 31, 1889. The South Fork Dam, near Johnstown, Pa., was built in 1852, 70 ft. high and 800 ft. long with puddle core, 20 ft. and 300 ft. wide at top and on bottom, respectively. The upper slope was 2:1, the lower, 1.5:1. Spillway size was 70 ft. by 8 ft. deep. Drainage area was 48 sq. mi. 4000 lives were lost. Property damaged was estimated about $9,000,000. Failure was due to inadequate spillway and overtopping of dam.--(h) Vol. 24, P. 431; E.B.R. Vol. 20, P. 15, 16, 25, 29, 30.

3. Broad Brook Dam, Ellington, Conn.--The flood

on Sept. 18, 1890 swept down the valley for 8 miles to the Conn. River, carrying out 5 dams, 2 railway trestles and 6 highways bridges.--E.N. Vol. 24, P. 267.

4. Spartansburg Dam, Pa.--The Spartansburg Dam, near Old City, Pa., failed on June 4, 1892. It was 180 ft. long and 10 ft. high and impounded a lake 1.5 miles long and 1 mile wide. The dam was of earth and rock, with center sheet piling was carried away. The waste weir other than a small flume, and the failure was caused by water running over the crest of the dam. --E.N. Vol. 47, P. 506; E.N. Vol. 27, PP. 584, 600.

5. Kittanning Point Reservoir, Pa.--Failed on May 20, 1894. The storage capacity of the reservoir was 65,000,000 gallons. It was built on 1879, 50 ft. high with 2.5:1, and 2:1 for the slopes of upstream and downstream, respectively, without core wall. The water flowed over the embankment for about 30 min., causing the partial failure of the reservoir. The spillway was 5.3 ft. in depth, by 34 ft. wide.--(a); (c)-1912; E.N. Vol. 31, PP. 473, 536.

6. Avoca Dam, Pa.--A dam of 350,000 gallon reservoir near Avoca, Pa. Failed on May 25, 1894, due to insufficient spillway.--(a); (b) E.N. Vol. 47, P. 506.

7. Oxford Dam, N. J.--A small mill dam at Oxford N. J. failed by heavy rains on June 18, 1896.--E.R. Vol. 34, PP. 80, 101.

8. Lewis Creek Dam, Staunton, Va.--The Lewis Creek Dam was wrecked by a storm on Oct. 1896.--E.R., Vol. 34, P. 342.

9. Boydstown Butter Co. Dam, Pa.--It was an earth dam, 28 ft. high and 310 ft. long, with timber core built in 1896 and failed in 1897. The slope of upstream face 2:1. The heavy rain washed out about 100 ft. embankment, either from overtopping or percolation along iron pipe line.--(c), 1912, P. 48.

10. Ward, Jefferson Co. Dam, Colo.--Failed on July 9, 1897. Heavy rains caused part of a reservoir covering 34 acres to give way, causing 20 ft.-flood in valley.--E.R., Vol. 36, P. 134.

11-12. Melzingah Dams, N. Y.--Two dams across the Melzingah Valley broked on July 14, 1897. The upper dam was about 250 ft. long, 30 ft. high. Upper slope was 2:5, lower, 5:3. The lower dam was about 800 ft. down stream and was about 220 ft. long, with both slopes about 2:1. The failure of the upper dam was due to overtopping and also inadequately construction; and resulted another disaster down stream.--E.R., Vol. 36, P. 135.

13. Grand Rapids City Res., Mich.--Built in 1874, 25 ft. high, 12 ft. wide at top with diameter 196 ft. at bottom. The clay core wall was lined on

inside with rubble masonry in cement. The inner slope was 1.5:1, the outer, 2:1. Failed on July 2, 1900, due to overtopping of crest.--(a); E.R., Vol. 42, P. 26; E.N., Vol. 44, P. 25.

14. West River Providence Dam, Rhode Island-- It was built in 1816, 17 ft. high with upper slope 1.5:1 and 55 ft. thick at base. Failed on March 11, 1901. Damage was to overtopping by flood wave from upper dam. --(a); E.R., Vol. 45, P. 212.

15. Middlefield Dam, Mass.--The rains on Apr. 19, 1901 caused a break in the dam of a reservoir at Middlefield, Mass. It was built in 1874, 30 ft. high and 500 ft. long with a masonry core wall. The fault lied in the fact that the waste gates were of antiquated design and could not be operated at the critical time.--E.R., Vol. 43, P. 425.

16. Pittston Res., Pa.--The Pittston Reservoir was built in 1870, 16 ft. high. The upper slope was 2:1 and the lower, 1.5:1. It failed in 1901 due to overtopping. No spillway.--(a); E.N., Vol. 46, P. 417.

17. Victor Dam, Colo.--Dam failed on May 19, 1901. 430 ft. long and 25 ft. high, due to inadequate spillway.--(a); (b); E.N., Vol. 47, P. 506; E.R., Vol. 43, P. 550.

18. Breakneck Run Dam, Pa.--Failed on May 29,

1902, by overtopping resulting from a cloudburst. It was built in 1887, 23 ft. high and 207 ft. long with concrete core wall carried into rock. Outer slope was 1.9:2, inner, 1.7:1.--(a); (c)-1914; E.N., Vol. 47, P. 425.

19. Utice Water Works Res., N. Y.--Failed on Sept. 16, 1902. It was built in 1853, 20 ft. high with upper slope 1:1. Water overflowed crest and cut through entire embankment. Failure was due to insufficient spillway capacity.--E.N. Vol. 48, P. 289.

20. Connellsville Res., Pa.--It was filled with earth, 25 ft. high failed in 1902, the section of wall was washed out by cloudburst.--E.N., Vol. 47, P. 425 .

21. Boydstown Dam, Pa.--Failure reoccurred in 1903, due to overtopping and inadequate spillway.--(a); (c)-1912, P. 50.

22. Fort Pitt Dams, Pa.--The Fort Pitt Dam, 10 ft. high, 170 ft. long, failed in 1903, due to overtopping and inadequate spillway.--(a); (c)-1912, P. 50.

23. Oakford Park Dam, Pa.--The dam was built in 1895, 25 ft. high and 321 ft. long with 2 masonry core wall of 3-4 ft. high. Failure took place on July 5, 1903, due to overtopping and inadequate spillway.--(a); (c)-1912; E.N., Vol. 50, P. 76; E.R., Vol. 48, P. 50.

24. Heledon Dam, N. J.--Failed in 1903. Number of mills were flooded, and forced to shut down.--E.N.,

Vol. 50, P. 578.

25. Six Mile Creek Dam, Ithaca, N. Y.--A small dam 15 ft. high near Ithaca was carried away on June 21, 1905 by a flood caused by a heavy rainfall.--E.N., Vol. 53, P. 693.

26-27. Leroux Creek Dams, Colo.--The upper Dam, 25 ft. high, failed by overtopping in July 1905. And the flood wave therefrom caused the lower dam to fail --(b); E.R., Vol. 22, P. 1905.

28. Hydraulic Co. Dam, Bridge Port, Conn.--It was built in 1855 and carried away in Aug. 1905, due to inadequate spillway.--E.R., Vol. 52, P. 189.

29. Sherburne Upper Dam, N. Y.--The dam was built in 1892, 34 ft. high and 300 ft. long with puddled core wall. Failure, on Sept. 3, 1905, was due to overtopping --(a); (b); E.N., Vol. 54, P. 274.

30. Sherburne Lower Dam, N. Y.--The Sherburne Upper Dam failure caused the lower dam to fail.--Item 29.

31. Yuba Dam, Calif.--The Barrier No. 1 on Yuba River failed on March 18, 1907, due to a flood of unprecedented magnitude. It was hydraulic filled type, built with two steps 14 ft. total height. The causes were: 1. the undermining of the structure by back-lash, 2. the wearing away of the concrete surface of the apron and thus permitting the rapid washing out of the

rubble rock fill.--(b); E.N., Vol. 58, P. 133.

32. Bishop Creek Dam, Calif.--Failed in 1909. Section was carried away by freshet.--E.R., Vol. 60, P. 166.

33. Laanecoorie Dam, Victoria, Aus.--Failed in 1909, due to erosion of downstream slope and overtopping. Spillway was inadequate. Upper slope was 3:1, lower, 2:1, and 3:1. Clay puddled core wall.--(m).

34. Lake George Dam, Colo.--It was 19 ft. high and 1,100 ft. long, failed on July 11, 1909.--(a); (f) 15th ed.; (h), Vol. 49

35. Dells Dam, Wis.--The Dells Dam was built in 1910, 45 ft. high, 597 ft. long, with a concrete core wall. The crest was of a 10 ft. depth. Both slopes were 2:1. During heavy rain, the water had raised to a height of 7 ft. or more above the crest of the concrete spillway at the east end of the dam. It failed on Oct. 6, 1911, due to overtopping and also due to the insufficient capacity of the spillway.--E.N., Vol. 66, PP. 452, 482, and 483.

36. Hatfield Dam, Wis.--The Hatfield Dam was about 6 mi. below the Dells Dam, built in 1907-08, 22 ft. high with a concrete spillway of 16 ft. depth. Both slopes were 2:1. It failed in Oct. 1911 due to inadequate spillway.--As Item 35.

37. Brookville Water Co. Dam, Pa.--It was built

in 1912, 16 ft. high, 360 ft. long with a concrete core wall. Both slopes were 2:1. The failure occurred in 1912 due to overtopping and inadequate spillway.--(a); (c); (b).

38. Union Bay Dam, B. C.--It was of earth fill with log crib, 20 ft. high, 565 ft. long, failed on Feb. 10, 1912, due to poor design and construction. No cutoff trenches in foundation, and no core wall. The spillway was not enough in storaging the usual flood. --(a); (b); E.N., Vol. 67, P. 667.

39. Winston Water Works Dam, N. Calif.--The dam was 25 ft. high and 300 ft. long of a masonry core wall built in 1904, failed on March 5, 1912, due to overtopping inadequate spillway and poor material in construction.--(a); E.N., Vol. 67, P. 667.

40. Credit River Dam, Erindale, Can.--The dam was about 700 ft. long, about 25 ft. high, with a core wall of concrete masonry. It failed on Apr. 7, 1912. The cause of the failure was due to insufficient spillway capacity to discharge the flood, resulting from the successive failures of the small dams above.--E.R., Vol. 65, P. 457.

41. Toronto Dam,Can.--Failed in 1912, due to overtopping. It was 35 ft. high, 700 ft. long with concrete core wall.--(b); E.R., Vol.65.

42. Mohawk Fishing Club Dam, Tiffin, Ohio--It was built about 400 ft. long and 18 ft. high at the

deepest section. The earth fill was made by terms and scrapers, no attempt being made to compact earth other than by driving over it. It failed in March 1913 due to overtopping. and inadequate spillway.--(g); E.N., Vol. 73, P. 1121.

43. Ovaca Dam, Tullahona, Tenn.--It was built in 1909, 16 ft. high, 175 ft. long, with concrete core wall. There was no fill placed on down stream side of core wall. Failure took place in 1904 due to overtopping.--(a); E.C., Vol. 42, P. 454.

44. Sepulveda Canyon Dam, Los Angeles County, Calif.--The dam consisted of a concrete wall, standing 60 ft. above a rotten bedrock of soft shale. The core wall was 2 ft. thick at top and no more than 3.5 ft. at any point. Both slopes were 1.5:1. The failed on Feb. 21, 1914 due to overtopping and inadequate spillway. --E.R., Vol. 74, P. 357.

45. Goose Creek Dam, S. Calif.--The dam was completed in 1903, 22 ft. high, 2300 ft. long. Both slopes were 3:1. Rainfall was unprecedented about 17 in. within 24 hrs. overtopping the dam, on July 14, 1916. --E.N., Vol. 76, P. 232; E.R., Vol. 74, P. 273.

46. Lake Toxaway Dam, N. Calif.--It was built in 1902, 385 ft. long on the crest, 62 ft. high at the lowest part, the slopes were 2:1. It set up on a solid rock foundation which had from one to two ft. of earth

cover. The rock was not stratified and had practically no open crevices. The heavy rain on Aug. 30, 1916 over flowed the dam and the dam failed. The spillway was insufficient.--E.N., Vol. 76, P. 331; E.R., Vol. 74, P. 273.

47. Veeders Pond Dam, Schenectady, N. Y.--The dam was 25-30 ft. high, about 150 ft. long. The side slopes were 1:1, built up of loose sand with a double plank cutoff wall near the upstream top angle. Heavy rainfall, on Oct. 20, 1916, made water overtop the dam in which there was no spillway. A waste gate on a 6-ft. pipe being the only outlet for the stored water.--E.N., Vol. 76, P. 816.

48. Schaeffer Dam, Colo.--The dam was 100 ft. high and about 1,100 ft. long with a core wall of concrete and timber. The upper slope was 3:1 and the lower, 2:1. The failure occurred in 1921, due to overtopping by the unprecedented runoff.--U.S.G.S., Water Supply, P. 487.

49. Willimansett Brook Dam, Mass.--Failed on July 17, 1922, due to overtopping of dam by flood from upper dam. It was built with puddle core wall.--E.N. R., Vol. 89, P. 121.

50. Ashland Dam, Iron River, Wis.--It was washed out on Dec. 12, 1922, due to the failure of a timber

dam above.--E.N.R., Vol. 90, P. 788.

51. Buckhorn Res., Long Mont., Colo.--Failed in 1923, due to overtopping and inadequate spillway.--(f) 22nd.

52. Missin Lake Dam, Horton, Kans.--This dam was built in 1923-24, with the upstream face protected from washing by a reinforced-concrete slab. Failure on June 18, 1925, due to insufficient spillway capacity, settlement of a section and overtopping of dam.--E.N.R., Vol. 95, P. 58.

53. Lake Coedy Dam, Dalgarrog, N. Wales--It failed in 1925 due to overtopping by flood resulting from the failure of another dam above.--E.N.R., Vol. 96, P. 12.

54. Lock Alpin Dam, Delhi, Mich.--The dam failed on Apr. 8, 1926, due to overtopping. Sudden thawing ice and snow caused inflow to exceed spillway capacity. It was about 25 ft. high with both slopes 2:1, the upstream slope was paved with stone.--E.N.R., Vol. 96, P. 924.

55. Lake Hemet Water Co. Dam, Calif.--It was built in 1923, 20 ft. high and 273 ft. long with a 8 ft. thick puddled core wall. Failure occurred on Feb. 16, 1927, due to overtopping.--E.N.R., Vol. 98, P. 423.

56. Wise River Dam, Mont.--It was a earth and rock filled dam, with plank facing. Failure took place

in 1927, due to high water cutting through bank at one end of dam.--E.N.R., Vol. 99, P. 196.

57. Maquoketa River Dam, Iowa--Completed in Jan, 1924, failed on June 1, 1927. It was an earth embankment without core, 20 ft. high and 450 ft. long. Failure happened where earth embankment joined the concrete dam. Embankment may have be come saturated from heavy rains.--E.N.R., Vol. 98, P. 1000.

58. Escanaba River Dams, Mich.--Two small dams on the Escanaba River, Mich. Failed on June 25, 1930, due to overflow at the end of the concrete spillway. They were about 15 to 20 years old.--E. N. R. , Vol. 106, P. 71.

59. Harrison Creek Dam, Georgia--A small earth dam, Harrison Dam failed in May 1931, due to overtopping by the flood caused by the failure of Beaver Creek Dam (Item 183),--E.N.R., Vol. 106, P. 824.

60. Holly Dams, Colo.--Two small dams were swept away by flood caused by heavy rain on Aug. 28, 1935. --E.N.R., Vol. 115, P. 341.

61. Elk City Dam, Okla.--This was of rolled fill type, 30 ft. high and 2019 ft. long, with a concrete core wall, upper slope was 3:1, lower, 2:1. Failed in 1936 due to inadequate spillway.--E.N.R., Vol. 116, P. 678.

62. Navigation Dam #4, Bracburn, Pa.--It failed in March 17-19, 1936, due to flood.--E.N.R., Vol. 116,

P. 631.

63. Emsworth Dam, Pittsburgh, Pa.--It failed in 1936, due to overtopping.--E.N.R., Vol. 116, P. 631.

64. Wagner Dam, Washington--It was of hydraulic fill type, 50 ft. high and failed in Apr. 1938, due to a fault in concrete spillway. Unusual snows in the watershed of the Loop Loop reservoir had melted repidly, making the flow on the top of the dam.--E.N.R., Vol. 120, P. 602.

65. Mount Lake State Park Dam, Luverne, Minn.--The dam failed on May 5, 1938, due to the flood water following a heavy rainstorm. A section of 20 ft. at one end of the dam and a 70-ft. section at the other were washed away.--E.N.R., Vol. 120, P. 698.

66. Killingworth Dam No. 1, Conn.--The dam failed partially on July 23, 1938. It was 18 ft. high with core wall stored water about 130,000,000 gall. Failure was due to overtopping and erosion cutting away support for the corewall east of the spillway. A section about 100 ft. long overturned.--E. N. R., Vol. 121, P. 101, and P. 129.

67. Short Mountain Creek Dam, Arkansas--The dam, which was about 75% completed at time of failure, was 740 ft. long and 57 ft. high. About a 125 ft. section was washed out on Apr. 16, 1939, when a recordbreaking rainfall of 5.35 in. in 15 hrs. caused the creek to

rise 5 ft. in 30 min.--E.N.R., Vol. 122, P. 535.

68. Martin Dovey Lame Dam, Palestein, Texas--A gap, 250 ft. wide of the dam was opened by heavy rain in Nov. 1940.--E.N.R., Vol. 125, P. 715.

69. Lake Dixie Dam, Texas--A section of about 40 ft. of the dam was washed away by two-day heavy rain in Nov. 1940.--E.N.R., Vol. 125, P. 715.

(2) Failure due to

Inadaquate Cutoffs & Porous Foundation

70. South Fork Dam, Pa.--The dam was built in 1853, 70 ft. high and 800 ft. long. Failure in 1862, due to leakage along conduit.--(a); (c), 1912.

71. New Bedford Dam, Acushnet River, Mass.--Failed in Feb. 1868. Built in 1866, with puddle core. Both slopes were 2:1, 25 ft. high and 600 ft. long. Freeboard 4 ft. and spillway 40 ft. Failure was due to leakage around the discharge culvert and water finding its way through fine sand below base of dam.--(h), Vol. 1, P. 57.

72. Bradford Dam, Sheffield, England--It was built in 1867, with puddled core wall, 90 ft. high; and failed in 1869, due to water following outlet pipes. --(h), Vol. 49, P. 1893.

73. Mill River Dam, Mass.--Failed on May 16, 1874, (built in 1865). Stone and concrete core, 43 ft. high, 500-600 ft. long. Core wall was set 5 ft. 9 in.

thick at bottom and 2 ft. at top. 143 lives lost and damage to property amounted to $1,000,000. Failure was due to the fact that water found passage under core wall.--(b); (h), Vol. 3, P. 118.

74. Dale Dyke Dam, England--It was of earth fill-type, 95 ft. high and 1254 ft. long, 12 ft. wide at top, 500 ft. at bottom with puddle core wall of width 4 ft. at top and 16 ft. at ground surface with a batter of 1.5 in. to 1 ft. on both faces. Failed in 1874 because of faulty design and construction. Inner partof dam was of rubble stone and shale. Outlet pipes were laid unprotected.--(a); (d).

75. Lynde Brook Dam, Mass.--It failed on March 29, 1876, 27 ft. high and 286 ft. long. Spillway was 25 ft. wide and core wall was made of masonry. The failure was due to the leakage around culvert passing through embankment.--(b); (h), Vol. 4, P. 244.

76. Staffordville Dam, Conn.--It was an earth embankment with masonry face wall, 26 ft. high, 150 ft. long, 4 ft. wide on top and 10 ft. on base. Failed on March 27, 1877.--(b); E.N., Vol. 4, P. 75; (h), Vol. 49, P. 1893.

77. Swansea Dam, S. Wales--It was built in 1867, 80 ft. high with puddled core, 425 ft. wide at base. Failed in Jan. 1879, due to a spring bursting through drains.--San. Eng. Vol. 3, P. 437.

78. Lynde Brook Dam, Worcester, Mass.--The failure of the Lynde Brook Dam occurred on March 29, 1879. It was 600-700 ft. long, 50 ft. wide on top, with a core wall of cobblestone and cement. Failure was believed due to that fact that the quicksand under pipe line allowed water to seep along pipe line.--(h), Vol. 4, P. 244-250.

79. Rock Springs Water Works, Wyo.--It failed on Feb. 2, 1888, due to leakage around the pipe through the dam.--(b); E.N., Vol. 19-20, P. 109.

80. Gunnison Dam, Colo.--It was 20 ft. high, failed in 1890, due to leakage along drain pipe.--(a); (b); E.N., Vol. 23, P. 529; Vol. 47, P. 507.

81. Lebanon Dam, Pa.--The Lebanon Dam was built on sandstone, 40 ft. high and 185 ft. long. Failed in 1893, due to leakage between sandstone and earth or through cracks in the sandstone.--E.R., Vol. 27, P. 475.

82. Portland Dam, Me.--It was built in 1888-89, 45 ft. high, 10 ft. wide on top. Both slopes were 1.5: 1. Failed in Aug. 1893, due to water following drain pipe.--(b); E.N., Vol. 30, PP. 105, 140, 156, 168.

83. Roxborough Res., Philadelphia, Pa.--Failed on July 18, 1894, due to leakage through interior lining.--(b); E.R., Vol. 31, P. 110.

84. Lancaster Res. Pa.--Failed on Oct. 14, 1894. Earth Res. with puddle core. Reservoir was two thirds

full at time of failure. Failure due to water leaking around outlet pipe.--(a); (b); E.R., Vol. 30, PP. 20, 336, 353.

85. Ansonia Res., Conn.--Failed on Nov. 3, 1894. A gap was reported to be about 200 ft. long and 35 ft. deep due to leakage along an old waste outlet pipe.-- E.R., Vol. 30, P. 388.

86. Castlewood Dam, Cherry Creek, Denver City, Calif.--70 ft. high, 600 ft. long rested on a dense sandy clay foundation, 5 to 22 ft. below the nature surface. Failed on Apr. 30, 1900, due to heavy rain. --E.R., Vol. 52, P. 533.

87. Wilmington Dam, Del.--The dam was built in 1864, and the earth embankment was raised 3 ft. 4 in. in 1887, 12 ft. of total height. Embankment was lined with clay and faced with brick, 40 ft. wide at base. It failed in Oct., 1900, due to leakage along pipes through bank.--(b); E.R., Vol. 42, Oct. 20, 1900.

88-89. West River Dams, Providence, Rhode Island --Two dams were built in 1860 with sand and gravel, failed on March 11, 1901. Upper dam was 17 ft. high, of slopes 2:1 and 74 ft. wide at base. The cause for the upper dam failure is believed to be that water found its way over the top close to a wooden sluiceway which combined both roll-way and flood gates,and also because of huge masses of ice. The failure of the

lower dam was mentioned in Item 14, p. 34.--E.R., Vol. 45, P. 554.

90. East Liverpool Res., Ohio--It was built in 1901, lined with 1.5 ft. concrete laid on 2.25 ft. of puddle clay, 23 ft. high, 273 ft. long and 146 ft. wide. Break occurred at time of first filling, when water reached a height of 17.4 ft. Failed on Oct. 13, 1901, due to leakage over pipe through embankment.--(a); (b); E.R., Vol. 44, P. 433, E.N., Vol. 47, P. 506.

91. Whichita Falls Dam, Texas.--Failed in 1901. This dam was built in 1901, earth fill. Leak developed during construction which was repaired, and another leak developed again and dam failed.--E.N., Vol. 45, P. 385.

92. Tupper Lake Dam, N. Y.--The Tupper Lake Dam, completed July, 1906, was equally divided between excavation and embankment . It was 150 ft. wide, 18 ft. high and 215 ft. long. Inner slope was 2:1, outer, 1.5:1. Top width was 10 ft. Failed in Dec., 1906, due to leakage along outlet pipe which was put through embankment during freezing weather.--E.N., Vol. 57, P. 49.

93. Zuni, Black Rock Dam, N. Mex.--The dam was built in 1907 in rock and hydraulic fill type, 70 ft. high and 720 ft. long, 6 ft. wide at top. The slopes for rock were: 5:1 and 1.25:1; for earth, 3:1. Failed in 1909, due to the fact that one abutment was not

carried far enough into the hill resulting in leakage through the hill.--(a); (b); E.N., Vol. 62, P. 597.

94. Melville Dam, Utah--The dam was built in 1907, 36 ft. high, 800 ft. long, 10 ft. wide at top with puddle core. The spillway was 96 ft. wide and 6 ft. deep. Upper slope was 1.5:1, lower, 3:1. Dam failed on June 15, 1909, due to the causes; 1. undermining, 2. downstream slope too steep, 3, the quicksand foundation became saturated and collapsed.--E.R., Vol. 36, P. 135; E.N., Vol. 38, P. 60.

95. Jumbo Dam, West Julesburg, Colo.--Failed on March 11, 1910. The dam was built in 1905, 35 ft. high, 12 ft. wide at top without core. The upper slope was 4:1; lower, 2:1. Failure was due to faulty foundation and due to the leak of cutoff walls.--(g); E.R., Vol. 63, P. 467.

96. Dalton Dam, N. Y.--The Dalton dam was built in 1910, 25 ft. high and 181 ft. long, with a concrete core wall, 5.5 ft. wide at bottom, 1.5 ft. at top, with slopes of 2.5:1 and 2:1. Failed Apr. 23, 1912, due to core wall built on glacial drift and water from the reservoir undermined it.--(a); E.N., Vol. 67, P. 900.

97. Ansonia Dam, Conn.--The dam was built in 1911, earth filled with concrete core wall, 20 ft. high and 150 ft. long, Failed May 28, 1912, due to the undermining of the retaining walls.--(b); E.N., Vol. 67, P.

1103, 1196.

98. Colo. Springs Res. #4, Colo.--Failed on June 22, 1912. It was filled with earth, with no core wall, 50 ft. high 1000 ft. long, 18 ft. wide at top,; the outer slope was 2.5:1, the inner, 1.5:1. Spillways was 40 ft. wide. Partial failure was due to numerous leaks through foundation.--(b); E.N., Vol. 68, P. 682.

99. Hornell Dam, N. Y.--It was built in 1912, with core wall. Failed on Sept., 1912, due to numerous leaks through foundation, although foundation was on bed rock.--(b); E.N., Vol. 68, P. 682.

100. Horse Creek Dam, Colo.--The dam was complete in 1912, earth filled with concrete facing, 40 ft. high and 5,100 ft. long, 16 ft. wide at top. The inner slope was 1.6:1. The outer slope was 2.5:1 for first 16 ft. and then changed to 1.5:1. 7 ft. was the depth of the freeboard. Failed on Jan 28, 1914, probably due to faulty foundation and due to leakage along conduit.--(a); (b); E.R., Vol. 69, P. 205.

101. Washita Dam, Okla.--It was an earth dam of 12 ft. high with concrete core wall. Failed in Feb. 1914, due to undermining of the core wall.--(b); E.R. March 7, 1914.

102. Hatchtown Res., Sevier River, Utah--The dam was completed in Nov. 1908, 62 ft. high and 780 ft. long; 20 ft. wide at top with puddle core. Upper slope

was 2;1 (paved) and the lower, 2.:1. Spillway was 80 ft. wide and 5 to 6 ft. deep. Res. capacity, 13,000 A.F. Failed on May 25, 1914, due to leakage from hill-side or leakage along conduit.--(a); (b); E.N., Vol. 75, P. 60.

103. Turlock Irrigation District Dam, Calif.--This irrigation dam was built in 1914 about 39 ft. high. Failed in the year of construction, 1914, due to leakage around outlet structure.--(b); E.N., July 6, 1914.

104. Lake George Dam, Colo.--Built in 1907, 19 ft. high and 1,100 ft. long with puddle core. Failed on July 11, 1914, due to lack of puddle trench or cut-off wall.--(a); (b); (h) Vol. 49, P. 1893.

105. Owens Res., Calif.--Built in 1914. Failed in the same year, due to leakage around outlet structure.--(g).

106. Weisse Dasse River Dam, Bohennia--The dam was about 41.5 ft. high, 800 ft. long with clay cutoff wall. Both slopes were 1.5:1. Spillway was 200 ft. long. Reservoir was 3/4 full at time of failure. It failed on Sept. 28, 1916, due to poor material and construction and due to the leakage along outlet.--E.N., Vol. 77, P. 139.

107. Willimansett Brook Dam, Mass.--The dam was built in 1910, 30 ft. high, and 300 ft. and 15 ft. wide

at top with concrete core wall. Failed on July 7, 1922 due to undermining by leaks or springs.--E.N.R., Vol. 89, P. 121.

108. French Landing Dam, Huron River, Mich.--The dam was built in Feb. 1925, with stone core wall paved on face of slope. Multiple arch dam with earth embankment on one side. The outer slope was 2.5:1 and the inner, 2:1. Failed on Apr. 13, 1925, due to seepage along drain and due to faulty foundation.--E.N.R., Vol. 94, P. 735.

109. Lake Engran Dam, London, England--Failed on Nov. 1925, due to leakage along outlet pipe.--E.L., Vol. Oct. 15, 1926, P. 484.

110. Corpus Christi (La Fruta) Dam, Texas--It was built in rolled fill type. The total crest length was 4080 ft. including the spillway length of 1250 ft. The max. height of embankment was 61 ft. The spillway was designed to take care of a flow of 400,000 sec-ft. The outer slope was 3:1 up to 19 ft. above the bottom and then changed to 2:1. The inner slope was 2:1. It failed on Nov. 23, 1930, due to the following causes:

a. The upstream cutoff wall did not penetrate impervious bed of clay. The seepage could take place between the bottom of the sheetpiling and the clay bed,

b. Abutment pulled away from spillway, and

c. Action of underground erosion.--E.N.R., Nov.

27, 1930, and Dec. 18, 1930.

111. Belle Fourche Dam, S. Dakote--It was 115 ft. high and 6500 ft. long, without core. Upstream side was paved with concrete with slope 2:1. Failed in 1933, caused by building up of hydrostatic pressure behind the concrete face the upstream side.--E.N.R., Vol. 111, P. 371.

112. Niobrara River Dam, Nebr.--It was 18 ft. high 1800 ft. long with 400 ft. concrete spillway section. Failed on Sept. 24, 1935. A 150 ft. concrete spillway section failed suddenly and almost as a unit. Immediately afterwards the floodgates collapsed. It was believed that the failure was caused by undermining of the soapstone rock on which the spillway section was built.--E.N.R., Vol. 117, P. 186; Vol. 117, P. 526.

113. Brokaw Dam, On the Wis. River, Wis.--28 ft. high and 800 ft. long with concrete core. Failed on May 29, 1938, due to high water resulting from spring rains and weakening of the foundation by erosion.--E.N.R., Vol. 120, P. 767.

114. Dry Creek Dam, near Jordan, Mont.--Failed on March 13, 1939, a 70-ft. section of the structure was carried away, due to the undermining of the sandstone formation under the dam.--E.N.R., Vol. 128, P. 407.

115. Sinker Creek Dam, Owyler County, Idaho--It

was filled with earth, 70 ft. high, 1100 ft. long, found on basalt bedrock with one verylow and ineffective cut-off wall not keyed into rock. Failed on June 19, 1943. --E.N.R., July 8, 1943.

(3) Failure due to Faulty Construction

116. Mud Pond Dam, Mass.--It was built in 1873, 15 ft. high, 325 ft. long, 28 ft. wide at bottom, and 6 ft. at top without core. Downstream slope was 3.5 to 2.5. Failed on Apr. 20, 1886, due to building it on the natural top soil (swampy ground in this case). Water seeped through the dry rock wall and earth fill. --(a); (b); E.N., Vol. 15-16, P. 295. E.R., Vol. 13, P. 560.

117. Snake Ravine Dam, San Joaquin Valley, Calif. --This was built with hydraulic fill method, 64 ft. high and 294 ft. long at crest. Slopes were 1.5:1 and 2:1. Failed on June 14, 1898, due to poor construction. --use too much fine clay.--(a); E.N., Vol.40, P. 242.

118. Lake Frances Dam, Lobbins Creek, Calif.-- Built in 1899, 50 ft. high 992 ft. long at top. Slopes were 2:1, and 3:1. Crest was 4 ft. above spillway level. Spillway was 40 ft. wide. Failed on Oct. 21, 1899, due to the fact that too much of material was dumped at random, perishable materials were not removed and seepage along outlet conduit.--(a); (e), P. 115;

(h), Vol. 58, P. 196.

119. Utice Water Works Res., N. Y.--Built in 1874, 70 ft. high and 150 ft. long. Width was 275 ft. at base, 20 ft. at top. Upper slope was 2:1, lower, 1.5:1. Failed on Sept. 16, 1902, due to poor material, slope being too steep, and poor construction.--practically no rolling or welting.--(a); E.N., Vol. 48, PP. 225, 290; E.R., Vol. 46, P. 290.

120. Green Lick Ren Dam, Pa.--Built in 1901, 60 ft. high, 850 ft. long, 12 ft. wide at top without core wall. Both sides of dam were covered with riprap. Failed on July 17, 1904, due to faulty foundation and leakage and due to that much of the embankment wasplaced while frozen.--(a); (c)-1912; E.N., Vol. 52, P. 107.

121. Riverside Dam, Colo.--It was built in 1909, 25 ft. high and 16 ft. wide on crest, outer slope, 1.5:1, and inner slope, 3:1. It failed in 1909 and 1910, due to cracking of concrete paving and sleughing of embankment.--(a); (f), 15th Ed.

122. Mohawk Fishing Club Dam, Tiffin, Ohio--It failed first time in 1913, and then was reconstructed, and failed again on Feb. 1, 1915, due to settlement and fill not properly contracted, resulting large slips on upstream face.--E.N., Vol. 73, P. 1121.

123. Lyman Dam, Little Colo. River, Aris.--It was completed in Aug. 1913, 65 ft. high, 840 ft. long

on crest, with puddle core 12 ft. wide, slopes 2:1. Built by farmers without engineering advice or supervision. Failed on Apr. 14, 1915, due to poor construction but would later have failed from overtopping.--(a); E.R., Vol. 71. P. 537; E.N., Vol. 73, P. 794.

124. Stanley Lake Dam, Colo.--Built in 1911, 113 ft. high and 6630 ft. long with puddle core 10 ft. wide at top and 70 ft. at bottom. Upstream slope was 3:1, and 2:1; and the downstream, 2:1. Failed on July 12, 1916, due to poor construction, fill not rolled or packed, trestle work left in dam. Core was not satisfied. There were large slips on upstream face.--E.N., Vol. 78, P. 440.

125. Mammoth Dam, Utah--Failed in June, 1917. Concrete core with buttresses, 70 ft. high. Very poor construction. Water washed around temporary wooden flume which was used as spillway.--E.N.R., Vol. 79; (i)-4th Ed. P. 1307.

126. Apishapa Dam, Fowler, Colo.--The concrete cutoff wall did not extend to top of dam, 115 ft. high; 585 ft. long; and 16 ft. wide at top. Freeboard was 7.8 ft. above spillway crest. Outer slope was 3:1, the inner, 2:1. Failed on Aug. 22, 1923, due to settlement cracks in earth forming water passages. Material was unsuited for fill.--(f), 22nd; E.N.R., Vol. 91, P. 357.

127. Gros Ventre Dam, Landslide, Wyo.--The dam

was 180 ft. high failed on May 18, 1926, due to saturation and seepage.--(g); E.N.R., Vol. 98, P. 878, 917.

128. Diandi Dam, Mcmahan Creek, Calif.--The dam was built in 1926, 50 ft. high; 340 ft. long and 10 ft. wide on crest. Failed in 1926, due to settlement.--(g).

129. Balton Dam, N. Y.--Failed on June 8, 1941, due to poor construction.--E.N.R., Vol. 130, P. 457.

(4) Failure Due to Faulty Design or Due to Too Steep Slopes

130. Water Works Co. Dam, Nebr.--Failed on Apr. 10, 1890, just completed. It was 17 ft. high and 8 ft. wide on the crest, outer slope was 1:1, inner, 1.5:1. Walls slid into reservoir, because of poor engineering. --(a); (b); E.N., Vol. 23, P. 377.

131. Kauffman Run Dam, Pa.--The dam was built in 1886, 55 ft. high and 800 ft. long, 20 ft. wide at top, with a puddle core wall. The outer slope was 2:1, the inner, 1.5:1. Failed in 1892, due to leakage occurred through embankment probably caused by excessive steepness of inner slope. Dam was rebuilt with concrete core wall.--(a); (c), 1912, P. 50.

132. Grass Valley Dam, Colo.--Built in 1891, 49 ft. high and 580 ft. long, 10 ft. wide on crest. The outer slope was 3:1, and the inner, 2:1. Failed in 1895, due to faulty design and construction.--(f).

133. North Dike, Wachusett, Mass.--It was built in 1900-05 with no core wall, 82 ft. high and about 10, 000 ft. long, outer slope was 2:1, the inner, 100:3. Failure would be due to too fine material and too steep inner slope to stand when being saturated. Failed on Apr. 11, 1907.--(a); E.N., Vol. 67, P. 464; (i), P. 1543.

134. Lebanon City Dam #2, Pa.--The dam was built in 1884, 39 ft. high and 700 ft. long without core wall. Failed in 1910, due to saturation and slopes too steep (inner slope: 1.5:1, outer, 2:1.) Repaired with down-stream slope 2:1.--(c), 1912, P. 63.

135. Lebanon Dam, Pa.--Built in 1884 and enlarged in 1910, 42 ft. high and 720 ft. long without core wall. Outer slope 2.3:1 and inner slope 2:1. Failed on Apr. 8 1912, due to sliping on outer slope, and being softened by rains.--(b); E.R., Apr. 24, 1912; E.N., Vol. 67, P. 86.

(5) Failure Due to Inadequate Means for Stream Control during Construction

136. Credit River Dam, Erindale, Ontario, Can.--Built in 1910 with concrete core wall, 35 ft. long. The whole dam was 700 ft. long and 50 ft. high. Concrete spillway was 96 ft. long and 6 ft. deep. Failed on March 7, 1910,due to flood water during construction, which could not be carried away fast enough.--(a); E.N., Vol. 63, P. 439.

137. Turkey Creek Dam, Colo.--Built in 1910, 106 ft. high and 770 ft. long, 22 ft. wide on crest. Outer slope was 1.5:1, the inner, 3:1. Failed in 1910 during construction by overtopping from excessive flood. Fill had reached height of 60 ft.--(f), 15th Ed.

138. Ketner Dam, Pa.--45 ft. high and 597 ft. long with concrete core wall, 16 ft. wide on crest. Outer slope was 2.5:1 and inner, 2:1. Failed in 1911 during construction due to flood.--(a); (c), 1912, P. 56.

139. Puddingstone Dam, Calif.--Failure was due to flood during construction resulting overtopping. Failed on Apr. 7, 1926.--(g); E.N., Vol. 96, PP. 665, and 913.

140. Peapack Brook Dam, Cladstone, N. J.--32 ft. high and 360 ft. long with concrete core wall. Base width was 40 ft. top width, 14 ft. Failed on Dec. 17, 1927, due to overtopping during construction.--E.N.R., Vol. 96, P. 116.

(6) Failure Due to Excessive Quantities of Clay or Other Classes of Fine Material

141. Prospect Dam, N. S. W.--This was a 80 ft. high dam with clay puddled core wall. Outer slope was 3:1, inner, 2:1. Failed in 1888, due to unsuitable material and excessive moisture causing upstream slope to slip into reservoir.--(m).

142. Turtle Creek Res., Dallas, Texas.--29 ft. high, 12 ft. wide on crest, without core wall. Both slopes were 2:1. Failed in 1891 due to excess clay. Dam settled on outer slope for about 300 ft. vertically. Brick and cement lining cracked.--(b); E.N., Vol. 25, P. 555; Vol. 26, P. 81.

143. Ketterling Dam, England--Built in 1905, 46 ft. high and 12 ft. wide on crest, with puddle core wall. Outer slope 3:1, inner, 2.25:1. Failed in Sept. 1905, due to settlement of puddle core during construction.--(b); E.N., Vol. 52, P. 365.

144. Santo Amaro Dam, Brazil--Hydraulic fill. 63 ft. high, and 5700 ft. long, 33 ft. wide on crest. Outer slope was 3:1, inner, 2:1. Failed in 1907, due to excess of clay in blanket which slipped over core wall during construction.--(i), P. 1546.

145. Necaxa Dam, Mex.--Failed on May 20, 1909 during construction. Hydraulic fill with clay core wall. 190ft. high, top wide 54 ft. Outer slope was 3:1, inner, 2:1. Soft clay core bulged.--(a); (b); E. N., Vol. 62, PP. 72, 99.

146. Gatun Dam, Panama--Hydraulic fill, 115 ft. high. Outer slope was 7.67:1 for 90 ft. and 4:1 for remainder; downstream slope, 8:1 for 30 ft., 16:1 to 60 ft.; 8:1, to 90., and 4:1, to top. Failed in 1912, due to internal liquid pressure causing a bulge upward

and outward for some 14 ft.--E.N., Vol. 66, P. 562, 577.

147. Calaveras Dam, Calif.--Hydraulic fill, 240 ft. high and 1300 ft. long, 25 ft. wide on crest, 1312 ft. at base. Outer slope was 3:1, inner, 2.5:1. Failed on March 24, 1918. Hydrostatic pressure of clay core pushed middle section of upstream side into reservoir. --E.N.R., Vol. 80, P. 679; E.N., Vol. 72, P. 692.

148. Linville Dam, N. Calif.--Failed in 1919, due to inernal liquid pressure during construction.--(j).

149. Garza Dam, Dallas, Tex.--Hydraulic fill, built in 1928, 35 ft. high and 11,000 ft. long, with gravel blanket on upstream slope 3:1. Failed in 1928, due to material, clay, which occurred in tough impervious balls. Embankment flattened during construction to slopes 10 to 15:1.--E.N.R., Vol. 100, P. 772.

150. Alexander Dam, Island of Kauai, Hawaii--Hydraulic fill, 95 ft. high, and 620 ft. long on crest. Thickness at base was 640 ft. Upstream slope was 3:1, downstream, 2:1. Earth core in the dam was chemically treated. Failed on March 26, 1930, due to pressure of semi-liquid mass causing central portion to flow away. The failure did not affect chemically treated material. --E.N.R., Vol. 104, PP. 665, 703.

(7) Failure Due to Ice-Pressure

151. Montreal Res., Quebec, Can.--Masonry wall backed by puddle and then with an earth and stone embankment. Failed in 1816, due to leakage caused by ice action near the high water line.--(b); E.N., Vol. 47, P. 507; E.R., Vol. 36, P. 456.

(8) Failure Due to Burrowing Rodents

152. Sheldon Dam, Conn.--Built in 1881 with sheet piling and clay puddle, 500 to 600 ft. long, 18 to 20 ft. high. Top width was 10 ft. Water face was covered with heavy riprap. Failed on Feb. 22, 1903, due to burrowing muskrats. The flood from this large dam overtopped a down-river masonry dam, 30 ft. high and 60 ft. long, and carried away about 10 ft. of its crest.--(a); (b); E.N., Vol. 49, P. 185.

153. Lake Avalon Dam, Pecos River, Carlsbad, N. Mex.--The dam was reconstructed in 1894, 48 ft. high, and 1380 ft. long, 43 ft. wide at top. Failed on Oct. 1, 1904, probably due to animals burrowing into east part of downstream side and weaking the earth facing. --(a); (b); E.N., Vol. 54, P. 9.

154. Hebron Dam, Maxwill, New Mex.--Built in 1913, 56 ft. high and 3700 ft. long, 12 ft. wide on crest and 183 ft. wide at base. Outer slope was 3:1,

inner, 1.5:1. Spillway was 203 ft. wide and 13 ft. below top of dam. Failed on May 2, 1914, due to water finding its way through gopher holes. A gap 200 ft. wide and 31 ft. high was washed out.--(a); (b); E.N., Vol. 69, P. 629.

(9) Failure Due to Faulty Foundation

155. Ashti Dam, India--Failed in 1883, 85 ft. high and 12,709 ft. long, with puddled core. Inner slope was protected by stone paving. Failure was due to saturation of foundation.--(d), P. 234; (h), Vol. 49, P. 1893.

156. Lafayette Dam, Calif.--Rolled earth fill, 140 ft. high, 30 ft. wide on crest with clay core wall. Outer slope was 3:1, and inner, 2.5:1. Failed on Sept. 17, 1928, due to elasticity of material under dam. The dam subsided 24 ft. during construction.--E.N.R., Vol. 102, P. 167.

157. Clendening Dam, Ohio--It was of 62 ft. height with core of impervious rolled material. Failed in 1934, due to slight shear of plastic embankment.--(l), P. 666.

158. Herrin Dam, Little Wolf Creek, Ill.-- 40 ft. high, and 700 ft. long, built with puddle core wall based on blue clay. Spillway was of good design and construction. Failed on June 22, 1935, probably due to

the settlement.--E.N.R., Vol. 116, P. 556.

159. La Regadera Dam, Colombia, S. Amer.--Failed in 1937, due to the plastic clay in foundation.--(l), P. 666.

160. Marshall Creek Dam, Kansas--Failure occurred in 1937, due to the plastic clay in foundation.--(n).

161. Wyandotte Dam, Kansas City, Con.--The dam was filled with earth, 84 ft. high and 550 ft. long. The dam slumpeg or dropped of the downstream bank. Foundation failed because of no chance being saturated either by rains or by impounded water.--E.N.R., Vol. 120, P. 431.

162. Fort Peck Dam, Mont.--This was of hydraulic fill. Its failure occurred on Sept. 21, 1938. Abutment failed due to weak shear resistance of weathered shale and bentonite seams in the foundation; upstream slid due to liquafaction of the material in the slide and uplift under the dam.--E.N.R., Vol. 121, P. 385.

163. Harfford Dike, Conn.--Failed on July 4, 1941. It was a typical shear failure by a circular slide through clay foundation due to overstress in the clay caused by adding of the highway fill.--E.N.R., Vol. 127, P. 142.

(10) Failure Due to Unstable or Weak Foundation

164. Empire Res., Colo.--Failed in 1909, due to crack in conduit instead of intake end. The dam was built in 1906, 30 ft. high without core wall.--(a); (f)-15th Ed.; (h), Vol. 49, P. 1892.

165. Table Rock Cove Dam, Greenville, S. Calif. --The dam was built in 1827, 140 ft. high, 750 ft. long Upstream slope was 2.5:1 and 3:1, paved with riprap. Downstream slope was 2:1. Crest width was 30 ft. Failed in 1928, due to break in a 24 ft. drain pipe through base dam. Breaks were caused by movement and pressure of dam.--E.N.R., Vol. 101, P. 750; Vol. 103, P. 934.

(11) Failure Due to Insufficient Provision against Erosion from Back Wash below Dam or Spillway

166. Lima Dam, Mont.--It was 40 ft. high and 110 ft. long and with masonry core wall. Failed in May, 1894. Spillway was washed out but dam was left intact. --(A); E.N., Vol. 47, P. 506; Vol. 31, P. 486.

167. Trout Lake Dam, Colo.--It was built in 1894, 19 ft. high and 600 ft. long; 6 ft. wide at top, without core wall. Both slopes were 2:1. Failed on Sept. 5, 1909, probably due to undermining of foundation by discharge from spillway. Flood was caused by the failure of Middle Dam.--(a); E.R., Vol. 60, P. 476.

168. Balsam Dam, Mohawk River, N. H.--It was 60 ft. high and 300 ft. long, with concrete core wall. Spillway was 8 ft. x 6 ft. Box culvert through dam. Failed on May 3, 1929, due to back-wash of discharge from spillway destroyed riprap.--E.N.R., Vol. 102, P. 885.

(12) Failure Due to Earthquake

169. San Andreas Dam, Calif.--It was built in 1868-70, 91 ft. high and 800 ft. long, and 20 ft. wide at top with puddled core wall tied to rock with concrete wall 3 ft. x 5 ft. Failed in 1906, due to earthquake. Fault line passed across east end, causing crack 2 in. to 3 in. wide along dam axis.--(i), P. 1542.

170. Sheffield Res., Santa Barbara, Calif.--It was of 30 ft. height and 20 ft. width at crest. Both slopes were 2.5:1. Upstream face was lined with 4 in. concrete. Failure was due to earthquake in 1925.--(g); E.N.R., Vol. 95, P. 194.

(12) Failure Due to Wind Action

171-172. Harlem River and Spayton Duyvil Creek Dams, N. Y.--These dams were 350 ft. long and 60 ft. wide at base and 30 ft. wide at top and 4 ft. above ordinary high water. Failed on Apr, 20, 1893 by overtop-

ping due to wind and flood tide causing rise of 12 ft. --E.N., Vol. 29, P. 385.

173. Minatare Dam, North Platte Project, Nebr.--Built in 1912-15, 64 ft. high and 3,700 ft. long filled with earth and rock. Slopes were 2:1 and 2.5:1, upstream face was paved with 8 in. concrete slabs, downstream was gravel. Failure happened in 1920, due to ~~that~~ wave action broke and entered concrete slabes washing out gravel and earth, causing slabes to settle further.--E. & C., Vol. 54, PP. 371-373.

174. Owl Creek Dam, Nisland, S. D.--The dam was 115 ft. high and 6,500 ft. long. Both slopes were 2:1. Failed on Apr. 13, 1912, due to wave action damaged paving on upstream slope.--E.N., Vol. 67, P. 925.

175. Fort Peck Dike.--It was of hydraulic fill type, the pool core of which was 7,200 ft. long 60 ft. wide and 5 ft. high. Failed in 1936 by overtopping caused by violent wind storm.--E.N.R., Vol. 116, P. 933.

(14) Failure Due to Miscellaneous Causes

176. Valvaraiso Dam, Chile--It was 56 ft. high, 49 ft. wide at top, failed in 1888 due to unknown cause.--E.R., Vol. 18, P. 270.

177. Mahoney City Water Co. Dam #2, Mahoney City, Pa.--The dam was built with no core wall. Inner slope was paved, outer slope was covered with large stones.

Base width was 130 ft. Top width was 25 ft. Failed on June 17, 1892. Cause unknown.--E.R., Vol. 26, P.54.

178. Alcyon Lake Dam, Pitman Crove, N. J.--Failed on June 18, 1896.--E.R., Vol. 34, P. 80.

179. Bonney Irr. Res., Colo.--It was built in 1901, 40 ft. high. Failed on Apr. 11, 1903. A 100 ft-section was broken.--(b); E.R., Vol. 47, P. 444.

180. Cache La Poudre Dam, Colo.--Failed in 1907. --(b); E.N., Vol. 72, P. 721.

181. Scofield, Dam, Utah--It was 70 ft. high, 130 ft. wide on crest, with reinforced concrete core wall. Failed on June 24, 1925, due to water being held too close to top of dike.--E.N., July 5, 1925.

182. Saluda Dam, Columbia, S. Calif.--It was 208 ft. high and 7,855 ft. long. Core wall was made of impervious material. Failure happened on Feb. 19, 1930 due to water from segregated pool which broke through downstream dike and eroded a gulley.--E.N.R., Vol. 104, P. 374.

183. Beaver Creek Dam, Calif.--This small dam failed in 1931, a 200 ft.-section was washed out.--E.N.R., May 14, 1931.

184. Tappem Dam, Ohio--It was built with core wall of rolled material 25% clay. Dam height was 52 ft. Failed in 1934, due to moment from excess consideration.--(j); (l), Vol. III. P. 660.

185. Polson Dam, Mont.--Failed on March 3, 1937. Slide was attributed to recomment thaws and frost which loosened the earth on the canyln walls.--E.N.R., Vol. 118, P. 386.

186. Anaconda Dam, Mont.--Failed on July 28, 1938.--E.N.R., Vol. 121, P. 126.

187. Pratt Fork Creek Dam, Athens County Ohio--It was filled with earth. Failed on Sept. 14, 1938.--E.N.R., Vol. 121, P. 341.

188. Acton Dam, Out.--Failed on March 16, 1946.--E.N.R., Vol. 136, P. 452.

189. Coety Dam, N. Wales, England--Failed in 1925.--(London) Engineering, Dec. 4, 1925.

(15) Failure of Bottom in Small Water Works Reservoirs

190. Conshohocken Hill Res., Pa.--No core wall. Failed in 1873, 1876, 1879, and 1886, due to bottom linking of clay and brick failed.--(b); E.N., Vol. 47, P. 507.

191. Knoxville Res., Tenn.--Puddled bottom of a double reservoir failed in 1883.--E.N., Vol. 47, P. 507.

192. Roanoke Reservoir, Va.--Failed in 1888. Bottom settled and caved in.--(b); E.N., Vol. 47, P.

507.

193. Miburn Res., N. Y.--Failed in Aug. 1893, due to leakage of puddle bottom.--(b); E.R., Vol. 47, P. 344.

194. Portland Res. #2, Ore.--Failed in 1894, due to concrete lining.--(b); E.R., Vol. 48, P. 128, 168.

195. Queen Lane Res., Pa.--Built in 1894. Failed in the same year, due to leakage through concrete lining.--(b); E.R., Vol. 31, P. 57.

V. FAILURES OF ROCK-FILL DAMS

16 rock-fill dams failed in the past. The causes of failures would be classified into 7 different types: 6 of these failures were due to insufficient spillway; 2, due to inadequate cutoffs, or seepage; 4, due to faulty construction and faulty design; 1, due to excessive quantities of clay; 1, due to burrowing rodents; and 1, due to insufficient provision against erosion. However, no rock-fill dams could be found in our record, the failures of which resulted from ice pressure, or from unstable foundation. For rock-fill dams, ample free board should always be provided and spillway is also of outstanding importance.

(1) Failure Due to Inadequate Spillway

196. Walnut Grove Dam, Prescott, Ariz.--It was built in 1887, 110 ft. high, 400 ft. long, and 140 ft. wide at base and 10 ft. at top. The upper slope was lined with timber. Failed on Feb. 22, 1890, due to overtopping resulted from inadequate spillway.--(a); (b); E.N., Vol. 23, PP. 193, 206, 225, 229, 328, 389, and 399; E.R., Vol. 21, P. 194.

197. Pecos River Dam, Eddy, New Mex.--It was built in 1890, 45 ft. high and 1,570 ft. long. The upper slope, faced with earth on a slope 2:1, was 1.5:1, and the lower, 1:1. Failed on Agu. 6, 1893, washed away by flood. Inadequate spillway.--(a); (b); E.R., Vol. 28, P. 202; E.N., Vol. 36, P. 181; Vol. 47, P. 507.

198. Blue Water Dam, Zuni Mts, New Mexico--It was built in 1908, 35 ft. high; 325 ft. long; 20 ft. wide at top with puddle core wall. Spillway was 25 ft. long. The outer slope was 2:1, the inner, 1.5:1. Each face was protected by 1 ft. of riprap. Failed on Sept. 6, 1909. Water overtopped dam due to inadequate spillway. --(b); E.N., Vol. 62, P. 353; E.R., Vol. 60, PP. 385, and 439.

199. Lower Otay Dam, San Diego, Calif.--Built in 1897, 130 ft. high, and 565 ft. long with steel dia-

phragm. The upper slope was 1.2:1, and the lower, 1:1. Upperstream was not made impervious. Top width was 6 ft. Failed on Jan. 27, 1916. The causes were believed to be: a. too small cross section for a rock fill structure; b. failed to pave downstream slope; c. inadequate spillway and d. that the amount of fine material in the fill was much greater than had been ordinarily supposed. --(a); (b); E.N., Vol. 75, P. 334; E.R., Vol. 73, P. 226.

200. Briseis Mine Dam, Derby, Tesmania--Failure was due to overtopping during unprecedented flood.--(m).

201. Cheesman Lake Dam, Colo.--Built in 1900, 210 ft. high and 600 ft. long, as proposed. Failed in 1900, due to flood water during construction.--(a); (e), P. 62.

(2) Failure Due to Inadequate Cutoffs & Porous Foundation

202. Spring Lake Dam, Fiskville, Rhode Island--It was built in 1887, 18 ft. high and 925 ft. long. Base width was 18 ft., and top width, 8 ft. Outer slope retained by stone wall and inner slope was paved with stone. Failed on Aug. 25, 1889 resulted from undermining .--E.N., Vol. 22, P. 193; E.R., Vol. 20, P.

184; Vol. 47, P. 506.

203. North Bowman Dam, Nevada Co., Calif.--Built in 1927, 170 ft. high, 370 ft. wide at base and 15 ft. at top, and paved with 8 in. concrete. Failed in 1928, due to leakage through walls of 6 ft. outlet tunnel. The failure showed the necessity for pressure grouting behind outlet walls and providing control at intake end.--E.N.R., Vol. 102, P. 904.

(3) Failure Due to Faulty Construction And Faulty Design

204. Keene Dam, N. H.--It was 15 ft. high. Failed on Apr. 1895, never was tight and never was protected from action of frost and ice, so that very heavy rain washed away a section.--E.R., Vol. 31, P. 380.

205. Pleasant Vally Dam, Fish Creek, Utah.--It was built in 1927, 64 ft. high, filled with earth and rock. Downstream slope was 1.5:1; upper slope was -.75:1 for rock fill, and 3:1, for earth. Failed on May 21, 1928, due to leakage occurred because of settlement cracks.--E.N.R., Vol. 100, P. 826.

206. Virgin River Dam, Lettlefield, Ariz.--Built in 1929, 120 ft. high, with both slopes 1:1. It was washed out in July, 1929 during construction due to poor construction and design.--E.N.R., Vol. 103, P. 526; W.C.N., Nov. 25, 1929.

207. San Gabriel Dam #2, Calif.--It was built from 1932, 265 ft. high and 580 ft. long and 750 ft. wide at base. Failed in Dec. 1933, due to heaving rain, considerable settlement occurred. Concrete facing slumped 12 ft. of vertical subsidence and due to absence of artifical wetting for settling purposes.--E.N.R., March 7, 1935, P. 343.

(4) Failure Due to Excessive Quantities of Clay

208. Eldon Weir, Victoria, Austratia--It was of 140 ft. high with concrete core wall, faced with clay. Slopes were 2:1. Failed in 1929 due to slumping of clay wall which pushed upstream rock-fill into reservoir.--(m).

(5) Failure Due to Burrowing Rodents

209. Lake Avalon Carlsbad Dam, New Mex.--Built in 1894, 43 ft. high, 1380 ft. long, upstream side was faced with earth of 3.5:1 slope. Downstream slope, 1.5:1 Failed on Oct. 1, 1904, due to burrowing animals or percolation near base.--(a); E.N., Vol. 54, P. 9.

(6) Failure Due to Miscellaneous Cause

210. Tallapoose River Dam, Ala.--It was built in 1901, 40 ft. high, 850 ft. long. Failure in 1901. Cause not given.--E.N., Vol. 47, P. 34, 52, 62, 70.

(7) Failure Due to Insufficient Provision against Erosion

211. Castlewood Dam, Cherry Creek, Denver, Calif. --It was one old structure of combined rock fill and masonry type, 92 ft. high, 600 ft. long, with overflow spillway 100 ft. long and 4 ft. deep paved with large masonry blocks. Failed on Aug. 3, 1933. The cause was due to erosion of lower toe, collapse of loose-rock fill composing mainbody of dam.--E.N.R., Aug. 10, 1933, P. 174.

VI. FAILURE OF MASONRY GRAVITY DAMS

There are 70 failures of masonry gravity dams recorded herein, and their causes are classified in 10 different types. Of these failures, 7 were due to inadequate spillway; 23, due to inadequate cutoffs or due to ineffective foundation; 7, due to poor construction; 10, due to poor design; 2, due to inadequate means for stream control, improper operation or inadequate maintenance; 1, due to burrowing rodents; 2, due to insufficient provision against erosion; and 10, due to miscellaneous causes. The lesson to be learned from these failures is that the foundation and the construction of the cutoff walls are of most importance for masonry dams. Next to the foundation, the design of dam section is also very important.

(1) Failure Due to Inadequate Spillway

212. Habra Dam, Algiers--It was a straight gravity built in 1873, 117 ft. high and 1,066 ft. long, 14 ft. wide at top and 88.4 ft., at base. Failed in 1881, due to spillway and faulty materials and construction.--(a); (b); (d); (e), P. 370.

213. Sheldon Dam, Conn.--It was built in 1881, 25-30 ft. high and 601 ft. long. Failed on Feb. 22, 1903, due to flood wave from a failed dam (Item 151).--(a); E.R., Vol. 47, P. 224.

214. Santa Catalina Dam, Durango, Mex.--About 40-49 ft. high, with rubble masonry spillway was about 50 ft. long. Failed in 1906, due to overtopping because of inadequate spillway.--(a); E.N., Vol. 56, P. 427.

215. Grandfather Falls, Co. Dam, Prairie River, Merrill, Wis.--With concrete and earth wing, failed on July 24, 1912, due to overtopped of earth wings by water 15 ft. above normal.--E.N., Vol. 68, PP. 233, 415.

216. Sweetwater Dam, San Diego Co. Calif.--It was 115 ft. high, 76 ft. wide at base, constructed with concrete. Failed in 1916 by overtopping resulted from inadequate spillway.--(a); E.R., Vol. 73, P. 225.

217. Molare Dam, Italy--The dam was arched in plan with a mean radious of 660 ft. 150 ft. high above

river bed; 125 ft. wide at base, 20 ft. at top; and 465 ft. long at crest. Failed on Aug. 13, 1935, during flood of unusual intensity. The causes were believed to be: 1. inadequate spillway; 2. sliding factor of the dam was too small.--E.N.R., Vol. 115, PP. 273, 608, and 618.

218. Killingworth Masonry Dam, Conn.--12 ft. high with core wall failed on July 23, 1938, due to heavy rain.--E.N.R., Vol. 121, PP. 101, 129.

(2) Failure Due to
Inadequate Cutoffs & Porous Foundation

219. Puentes Dam, Gaudalution River, Spain--It was built 1791, 164 ft. high 925 ft. long, 145 ft. wide at base and 36 ft. at top with rubble masonry faced with cut stone. Failed in 1802, due to pile and earth foundation was undermined.--(a); (b); (c).

220. Colerum Upper Dam, India--It was built in 1836, 7.4 ft. high and founded on walls sunk 6 ft. in river-bed. Failed in 1873, due to foundation undermined by leakage.--(i), P. 1550

221. Housatonic Dam, Birmingham, Conn.--Built in 1869, curved in plan, 40 ft. high and 636 ft. long, 25 ft. wide at base and 8 ft. at top. Failed in Jan. 1891, due to undermining of the rock fill.--(a); E.N.,Vol.

25, P. 279.

222. Des Moines Dam, Water Power Co., Iowa--Failed in 1893, due to ice, undermining, and faulty construction--(a); (b); E.N., Vol. 47, P. 507; E.R., Vol. 27, P. 400.

223. Angles Dam, Calaveras Co., Calif.--52 ft. high and 400 ft. long, connected with earth dike; 3 ft. wide at top and 35 ft. at bottom. Failed on Apr. 10, 1895 caused from undermining.--(a); (b); E.N., Vol. 23, P. 307; E.N., Vol. 47, P. 507.

224. Austin Dam, Colorado River, Tex.--Built in 1892, 60 ft. high, and 1,275 ft. long, 66 ft. wide at base, and 18 ft. wide at top. Failed on Apr. 7, 1900, due to poor design and faulty foundation. Sliding was probably due to uplift and back-wash.--(a); (b); E.R., Vol. 41, PP. 240, 372, 467, 480, and 554; E.N., Vol. 43, PP. 135, 244, 250.

225. Roxbury Dam, Vt.--It was built in 1870, made of stone laid up dry. 46 ft. long and 24 ft. high. 8 ft. wide at top and 14 ft. at bottom. It was faced with 2 thicknesses of boards. There was a plank facing and crest. Failed on Apr. 1, 1903, due to poor gravel foundation.--(a); E.N., Vol. 49, PP. 313, 504, 547.

226. Fall River Dam, Hot Spring, S. Dak.--It was built with concrete. An old wooden dam above gave way causing this dam to slide in spring of 1908, pro-

bably due to uplift in rocks.--E.R., Vol. 57, PP. 662, 795; Vol. 58, P. 55.

227. Fertile Dam, Minn.--Built with concrete. Failed in the first week of Apr. 1910, caused from the foundation not sunk deep enough.--E.N., Vol. 63, P. 506.

228. Bro. Valley Coal Co. Dam, Macdonalton, Pa. --Built in 1911 with concrete, 16 ft. high, 419 ft. long 13 ft. wide at bottom and 3 ft. at top, based on clay foundation. Failed in 1911, due to undermining and material and construction.--(a); (e)-1912, P. 66; E.N., Vol. 64, PP. 550, and 591.

229. Oswego River Dam, N. Y.--Built in 1870 resting on a crib sunk in gravel, 14 ft. high and 360 ft. long at crest, with timber apron downstream side. Failed on Apr. 1, 1912 by undermining from leakage.--(a); E.R., Vol. 65, P. 401.

230. Owasco Lake Dam, Auburn, N. Y.--Built in 1860, 10 ft. high, with rectangular gravity section. Spillway was 85 ft. long. Failed on Apr. 5, 1912, due to undermining after a prolonged period of leakage, and lack of repairs.--(b); E.R., Vol. 65, P. 476.

231. Bow River Dam, Namaka, Alberta, Can.--Concrete dam resting on gravel foundation which was undermined after penetrated a fracture in the inner apron. Fracture resulted from ice thrust during the previous

winter. Failed on July 15, 1912.--(b); E.R., Vol. 66, P. 376.

232. Nashville Dam, Tenn.--Completed in 1889, 33 ft. high and 22 ft. wide at base and 8 ft. at top. Masonry wall rested on limestone foundation. Failed on Nov. 5, 1912. Dam slid out together with a section of the foundation, resulted from water saturated clay seam.--(b); E.R., Vol. 66, P. 539; E.N., Vol. 68, P. 922.

233. Cayuga and Sececa Canal Dam #2, N. Y.--Completed in Aug. 1915, 24 ft. high and 475 ft. long, with cutoff wall carried 50 ft. into soft shale bank. Concrete dam with earth filled section on south end. It was blowout on Sept. 3, 1915, due to inadequate cut-off walls.--(a); E.N., Vol. 74, P. 570; Vol. 75, P. 500.

234. Salt River Diversion Dam, Ariz.--Built of rubble concrete, 12 ft. high, and 400 ft. long, 18 ft. wide at base, founded on porous foundation. Rock fill on upstream side paved with concrete. Undermined from back-wash on Jan. 28, 1916, due to lack of cutoff walls. --(a); E.N., Vol. 75, PP. 974, 975.

235. Moose Jaw River Dam, Can. Pac. R. R., Saskatcheman, Can.--300 ft. long founded on clay. Downstream face was protected with riprap which was washed away by 6 ft.-water overtop on Apr. 24, 1916.--(a); E. R., Vol. 73, PP. 624, and 667.

236. Coon Rapids Dam, Miss. River, Minn.--Completed in 1914, 21 ft. high, 2,000 ft. long, 27 ft. wide at base. It was washed out through pile foundation, on Sept. 1, 1917.--E.N.R., Vol. 81, P. 186.

237. Hill Dam, N. H.--Concrete dam, 35 ft. high and 100 ft. long, completed five years before failure. Failed on May 29, 1918, due to the following causes: 1. foundation was not suitable; 2. too light cross-section; and 3. poor construction.--E.N.R., Vol. 80, P. 1104.

238. Lake Eigian Dam, Wales--Built in 1911, 20 ft. high, about 3/4 mile long, 10 ft. wide at base and 4.5 ft. at top. Conrete dam founded on a glacial deposit of hard blue clay. Failed on Nov. 2, 1925, due to 1. footings not deep enough, 2. poor concrete, 3. poor foundation.--E.N.R., Vol. 96, P. 12; Vol. 97, P. 873.

239. Cross-Bois Dam, France--Built from 1830-39, 96 ft. high and 1,805 ft. long, 21 ft. wide at top, 52 ft. at base and rested on soft rock. Failed was due to poor foundation.--(d); (i), P. 1523.

240. Yellow River Dam, Necedah, Wis.--Concrete dam built on sand. Failed about in 1905. Water forced through sand under foundation, resulting in settling of dam.--E.R., Vol. 52, P. 533.

241, Ortighito Dam, Italy--Failed in 1935, due to erosion.--(London) Engineering, Aug. 13, 1935.

(3) Failure Due to Poor Construction

242. Little Rock Dam, Ark.--Built in 1887, 36 ft. high. Failed in 1887, due to poor construction.--E.B. R., Vol. 16, PP. 653, 673, 685; Vol. 17, P. 113.

243. Lynx Creek Dam, Prescott, Ariz.--Failed in 1891, due to lean mortar. It was 28 ft. high and 150 ft. long; 28 ft. wide at base and 12 ft. at top.--(a); E.N., Vol. 39, P. 362.

244. Portland Dam, Mex.--Built in 1890, about 100 ft. long and 17 ft. high. Failed in 1891, dueto poor construction, and too weak bond between courses. --(a); E.N., Vol. 25, P. 279.

245. Columbus Power Co. Dam, Chattahoochee River, Calif.--Built in 1901, 30 ft. high and 850 ft. long; 27 ft. wide at base, and 10 ft., at top. Failed on Dec. 29, 1901,due to poor construction and weak lond. --(a); E.N., Vol. 47, PP. 34, and 62.

246. Lincoln Pond Dam, Black River, N. Y.--Constructed in 1909. Built of cobblestone, cement and stone, 25 ft. high, and 250 ft. long. Failed on May 20, 1912, due to sliding on smooth foundation.--(b); E.N., Vol. 67, P. 1099.

247. Colonial Dam #4, Grindstone, Pa.--Built in 1906, with concrete, 31 ft. high, and 206 ft. long.

Failed in 1912 at construction joints, due to poor construction.--(a); (c)-1914, P. 45.

248. Hannawa Falls Dam, N. Y.--Built in 1899 with cyclopean masonry core, faced with 2 ft. masonry downstream and 3 ft. rubbled on upstream. Failed in 1914, due to poor design and construction.--(c)

(4) Failure Due to Faulty Design and Section too Light

249. Bouzey Dam, France--Built in 1878-81, 48 ft. high, and 1,700 ft. long; the width at base was 57 ft. Failed on Apr, 27, 1895 by slipping and overturning for length of 558 ft. due to tension at upstream face.--(a); (d); (i), P. 1524; E.N., Vol. 31, P. 399.

250. Lower Tallassee Dam, Tallapoosa River, Ala. --Built in 1901, 30 ft. high, 1,300 ft. long, 23 ft. wide at base, and 6 ft. at top. Failed during construction on Dec. 29, 1901, due to poor design.--Section too light. Water was 6 ft. 8 in. deep on crest when it failed.--(a); E.N., Vol. 47, P. 130.

251. Winston Dam, N. Calif.--Build in 1882-84, 34 ft. high, 3 ft. wide at top, 18 ft. at base. Constructed with brick. Wall overturned on Nov. 2, 1904, due to poor design.--(b); E.N., Vol. 52, PP. 430, 444.

252. Water Supply Dam, Musootatuck River, N.

Vernon, India--It was built in 1909, and 130 ft. long, 8 ft. high, with concrete wall. Upstream side was filled with riprap.--Failed in 1910, due to poor design.--(a); E.N., Vol. 68, P. 1024.

253. Conodoguinet Creek Dam, Shippensburg, Pa. --Built in 1911 with concrete, 11 ft. high, 2,900 ft. long, 4-5 ft. wide at base, 2-3 ft. at top. Upstream was filled with earth and gravel. Failed on Jan. 17, 1912, due to ice pressure and poor design and construction. Wall overturned.--(a); E.R., Vol. 66, P. 79.

254. Olympic Power Co. Dam, Elwha River, Port Angeles, Wash.--Concrete dam, built in 1912, 130 ft. high, 97 ft. wide at base, and 14 ft. at top. Failed on Oct. 30, 1912, due to poor design and engineering. A blowout of 40 ft. wide and 60 ft. deep took place through gravel, undermined the dam.--(a); E.N., Vol. 68, PP. 1072, 1232; E.R., Vol. 66, P. 600.

255. Namaka Dam, Medicine Hat, Alberta, Can.--It was a concrete gravity weir, 20 ft. high and 500 ft. long. Failed on June 15, 1915, due to poor design, and foundation not set on rock.--E.N., Vol. 72, P. 354; Vol. 75, P. 1070.

256. Prosser Dam, Truckee, Calif.--Concrete dam, 35 ft. high and 100 ft. long, 3 ft. wide at base and 2 ft. at top. Failed in spring, 1928. Section was too light, due to poor design.--E.N.R., Vol. 101, P. 318.

257. North Fork Dam, Danville, Ill.--Built in 1903, and raised in 1910, of concrete, 12 ft. high, and 174 ft. long, with 3 ft. flashboards, founded on rock about 3 ft. or 4 ft. below stream bed. Failed on May 21, 1930. Strain on dam caused concrete to c crack. Parts of dam slid on base, others overturned. Design was poor for extra 3 ft. of height.--E.N.R., Vol. 104, P. 945.

258. St. Francis Dam, Saugas, Calif.--Built in 1926 of concrete curved type. 204 ft. high 650 ft. long, 153 ft. wide at base, with radius 505 ft. for upstream face. Failed on March 13, 1928, due to faulty foundation and incorrect designing.--E.N.R., Vol. 100, PP. 456, 466, 517, 527, 553, 605, and 639.

(5) Failure Due to Inadequate Means for Stream Control During Construction

259. Del Gasco Dam, Gaudarrama River, Spain--Built in 1788-89, 236 ft. wide at base and 13 ft. at top, filled with rock and clay. It was 305 ft. high, and 823 ft. long. Failed in 1799 by overtopping during construction at height of 187 ft.--(a); (b); (d), P. 59.

260. Wisconsin River Dam, Rothchild, Wis.--It was a concrete dam with sheet piling driven to bedrock 42 ft. below. Failed in 1912, due to washing away of sand banks on one side during construction.--E.N., Vol.

68, PP. 233, 415, and 541.

(6) Failure Due to Ice Pressure

261. St. Anthony Falls Dam, Minneapolis, Minn.--Built in 1893-94, 18 ft. high, 366 ft. long, of sandstone masonry. Failed on Apr. 30, 1897, due to ice gorge against green masonry.--(a); E.N., Vol. 37, P. 290.

262. Minneapolis Dam, Minn.--Built with coursed ashlar sandstone masonry, 18 ft. high, 525 ft. long, 12 ft. wide at base and 5.25 ft. at top. Failed on Apr. 30, 1899 by sliding due to ice pressure.--(a); (b); E. N., Vol. 41, P. 307.

263. Whiting St. Res., Holyoke, Mass.--21 ft. high, 1773 ft. long, 15 ft. wide at base, 7 ft. at top. Earth fill against inner side. Failed in 1902, due to ice pressure, evidenced by leaks at base.--E.N., Vol. 47, P. 221.

264. Chambly Dam, Richelieu River, Montral, P. Q.--Failed on Nov. 17, 1900, It was a concrete dam of a height sufficient to get a head of 28 ft. in the power house, founded on shale rock. Failure was caused by poor foundation and ice pressure.--E.R., Feb. 16, 1901, P. 149.

265. Rockport Dam, N. Y.--21 ft. high, 150 ft. long, 15 ft. wide at base, and 3 ft. at top. Failed on

Apr. 8, 1912 from over throwing by spring freshet. Dam was weakened by pressure of heavy ice jam during winter. --(a); (b); E.R., Vol. 65, P. 681.

266. Saranac River Dam, Manisonville, N. Y.--It was built in 1895, 45 ft. high, and 152 ft. long, with two walls with cap of concrete. Lower side was faced with concrete. Failure occurred on June 16, 1912. The spillway of 80 ft. long and 4.5 ft. deep had moved slightly downstream and cracks had developed in the face of the structure on the lower side. The movement was due to the formation of ice in reservoir.--(a); E. R., Vol. 65, P. 94.

(7) Failure Due to Improper Operation or Inadequate Maintenance

267. City Dam, Fergus Falls, Minn.--Built in 1908 of concrete on clay, 28 ft. high 150 ft. long. Failed on Sept. 24, 1909, due to spring under foundation and stopping of drain pipe by city officials.--(a); E.N., Vol. 62, PP. 391, 393, 477, and 497.

268. Kennebec River Dam, Me.--Built in 1896, 12 ft. high with 5 ft. flashboards. Failed on Dec. 13, 1928, due to leverage action of high flashboards.--E.N.R., Vol. 101, Dec. 20.

(8) Failure Due to Burrowing Rodents

269. Manchester Dam, Conn.--29 ft. high and 175 ft. long. Failed on March 12, 1902. Dam slid and overtopped due to muskrats burrowing under foundation. --(b); E.R., Vol. 45, P. 580.

(9) Failure Due to Insufficient Provision Against Erosion

270. Traverse City Dam, Mich.--Built in 1904 with concrete. Failed on Aug. 23, 1907, due to scouring of foundation or backwash.--E.N.,Vol. 58, P. 265.

271. Riverside Dam, Indianapolis, Ind.--Built in 1899 of concrete with bedford stone facings. Wing wall failed in 1912, due to scour on downstream side from spillway water.--E.N., Vol. 68, P. 852; E.&C. Vol. 35, P. 492.

(10) Failure Due to Miscellaneous Causes

272. Grancheurfas Dam, Algiers--Built in 1884, 131 ft. high, 508 ft. long, 13 ft. wide at top and 134 ft. at base. Failed in 1885.--(i), P. 1524.

273. Mahnuddee Weir, India--It rested on earth foundation, 6400 ft. long with folding shutter 3 ft. faced with rubble stone. Failed in 1886, causes were not given.--(i), P. 1550.

274. Stephenson Creek Dam Presno, Calif.--37 ft. high, 200 ft. long, and 40 ft. wide at base, failed in 1892,--E.N., Vol. 29, P. 25.

275. Austin Dam, Texas--Completed in 1893, 68 ft. high, 1,275 ft. Failed in 1893, due to water flowing through a crevice which caused a portion of dam to settle and break.--E.N., Vol. 29, PP. 545, 618; Vol. 30 P. 78.

276. Scranton Dam, Pa.--It was built of rubble masonry dressed with graite, face filled with concrete 10 ft. wide at base. Failed on Oct. 10, 1895. Cause of failure was not given.--(b); E.N., Vol. 32, P. 365.

277. Power Co. Dam, Tampa, Fla.--Built with concrete masonry and weir, 22 ft. high, 600 ft. long. Failed on Dec. 13, 1898. Dynamited by persons opposed to its construction.--E.R., Vol. 39, P. 94.

278. Narora Weir, India,--Built in 1877, 3,800 ft. long, 8 ft. wide at base, with brick overflow, rested on earth foundation. Crest was covered with ashlar masonry. Failed in 1898. Crest covering was destroyed.--(d), P. 406.

279. Raquette River Dam, Hannawa Falls, N. Y.--35 ft. high, 325 ft. long, with masonry crest designed to act as waste weir for floods. Failure took place on Apr. 18, 1900, due to the failure of the temporary earth

dike at upper end of headrace.--E.N., Vol. 43, PP. 277, and 307.

280. Seneca River Dam, Anderson, S. Calif.--Masonry and concrete dam, 42 ft. high, 8 ft. wide at top, and 25 ft. at base. Construction was completed in 1897, and then it was raised 22 ft. in 1901. Failed on Dec. 29, 1901. High water sheared off new section, when water was 6 ft. over dam.--(a); E.N., Vol. 47, PP. 34, 52.

281. Criffin Dam, Pa.--62 ft. high, 284 ft. long, 4 ft. wide at top, and 44 ft. wide at base, curved in plan with radius 400 ft. At first leaks appeared near ends.--(i), P. 1529.

VII. FAILURES OF ARCH DAMS

There have been very few failures of arch dams, partly because of the comparatively recent construction, of this type of dam; partly because of the relatively large factor of safety used in their design; and partly because of their use on good foundations only.

9 failures of arch dams will be stated, one of them was caused by overtopping by large flood, probably due to inadequate spillway; 2, due to poor constrction; one, due to faulty design; 2, due to ice pressure; and three due to weak foundation. It is to be noted

that for arch dams the foundation treatment is also of excellent importance.

(1) Failure Due to Inadequate Spillway

282. Elche Dam, Rio Vinalapo, Spain--Built in 16 th century. Arched masonry overflow dam, 76 ft. high, 230 ft. long at crest. Upstream radius 205 ft. faced with rubble cut stone. Failed in 1836 from overtopping by large flood.--(b); (d); (e); (i), P. 1537.

(2) Failure Due to Poor Construction

283. Lake Gleno Dam, Dezzo River, Italy--It was of multiple arch on masonry gravity section base, built in 1921, 143 ft. high, 863 ft. long. Failed on Dec. 1, 1923, due to poor construction. Line mortar in base masonry, poor concrete, unwashed aggregate, poor reinforcing in buttresses and lack of engineering supervision.--E.N.R., Vol. 92, PP. 182, 486, 501, and 1018.

284. Manitou Dam, Colo.--Concrete arch dam, 50 ft. high, and 300 ft. long. Failed in 1924, due to poor concrete.--E.N.R., Vol. 95, P. 953.

(3) Failure Due to Faulty Design

285. Lake Pleasant Dam, Agula River, Ariz.--Completed in Sept. 1927. Multiple arch with distance of 60 ft. from center to center, 154 ft. high, and 2,146

ft. long. Failed in 1928, due to buttresses cracked. Spillway was cut down.--E.N.R., Vol. 102, PP. 116, 257, and 275.

(4) Failure Due to Ice Pressure

286. Gem Lake, Calif.--Multiple arch, built in 1917, 84 ft. high, 688 ft. long. Failed in 1925 from disintegrating probably due to ice.--E.N.R., Vol.95 P. 22.

287. Allard Dam, Lake Quebec, St. Louis, Can.--Built of buttresses type, 43 ft. high, 602 ft. long, with 32 piers and 2 core walls 10 ft. deep at heel and toe, since 1918. Failure in 1928, from spalling of concrete due to frost action. Temperature ranged between -30 to 95° F.--Can. E., Vol. 58, No. 3, PP. 141, and 143.

(5) Failure Due to Weak Foundation

288. Lake Lanier Dam, Vaughn Creek, N. Colif.--Arch dam with 150 ft. constant radius, 62 ft. high, 236 ft. long, 12.5 ft. wide at base, and 1 ft. at top. Completed on 1925, failed on Jan. 21, 1926. Washing one of cyclopean masonry abutments which rested on soft and decomposed rock was washed out.--E.N.R., Vol. 96, P. 172; Vol. 97, P. 616.

289. Moyie River Dam, Bonners Ferry, Ida.--It

was a thin arch dam, 53 ft. high, 154 ft. long, about 24-64 ft. wide. Failed before Oct. 14, 1926 from undermining of spillway, due to soft and stratified rock. --E.N.R., Vol. 97, P. 616.

290. Hodges Dam, San Dieguito River, San Diego-- It was light multiple-arch dam with concrete buttresses with max. height 130 ft. above stream bed, 616 ft. long at rested on solid rock. It consisted of a number of concrete buttresses slightly more than 4 ft. thick at stream bed and only 18 in. at top. Cracks occurred in 1936, which were different in width openings of 3/8 to 1/4 in. and were changeable daily. The cracking was due entirely to volume change on the concrete in hardening and later under temperature change.--E.N.R., Nov. 5, 1936, P. 645.

VIII. FAILURES OF REINFORCED CONCRETE DAMS

There were 9 reinforced concrete dams failed from two different types of causes. 8 of these failures were due to inadequate cutoff walls or porous foundation and one was due to faulty means for stream control during construction. For this type of dam, failure would take place almost always due to faulty foundation.

(1) Failure Due to Inadequte Cutoffs & Porous Foundation

291. Ashley Dam, Pittsfield, Mass.--It belonged to Ambursen type built in 1908, 40 ft. high and 400 ft. long with a spillway of 48 ft. long. Failed on Jan. 7 1909, due to undermining inadequate cutoff walls.--(a); (b); E.N., Vol. 61, P. 345.

292. Geo. Sweet Mfg. Co. Dam, Canaseraga creek, N. Y.--Built in reinforced buttresses type with earth dike at end, 15 ft. high and 368 ft. long. Failed in 1909. The causes were believed being poor construction, poor design and loose gravel foundation.--(a); E.R., Vol. 61, P. 24.

293. Austin Dam, Freeman's Run, Pa.--Completed Dec. 1909, 50 ft. high, 554 ft. long, 30 ft. wide at base, and 2.5 ft. at top with spillway 50 ft. long and 30 in. deep. Failed on Jan. 17, 1910. Dam slided out of bottom 18 in. and 31 in. at top. Failure was due to poor construction and poor foundation.--E.N., Vol. 63, P. 321.

294. Austin Dam, Freeman's Run, Pa.--Failed on Sept. 30,1911 from sliding and breaking, due to poor foundation.--(a); (c), 1912; E.N., Vol. 66, PP. 410, 419, 462, 544; E.R., Vol. 64, PP. 429, 442, 446, 578.

295. Lake Leigh Dam, Pa.--It was of Ambursen type, built in 1906, 32 ft. high, and 320 ft. long. Failed in 1911, due to faulty foundation resulting in leakage under dam.--(a); (c), 1912, P. 61.

296. Yahara River Dam, Junesville, Wis.--9 ft. high, and 100 ft. long, failed in 1912, from undermining due to faulty foundation.--(b); E.N., Vol. 65, P. 45.

297. Stoney River Dam, Davis, W. Va.--Completed in 1913, Ambursen type, 51 ft. high, and 1,065 ft. long. Failed on Jan. 15, 1914, from undermining due to cutoffs not carried sufficient deep.--(a); (b); E.N., Vol. 71, P. 211.

298. Plattsburg Dam #3, West Brook, N. Y.--Completed in 1915, Ambursen type, 35 ft. high, and 330 ft. long and 42 ft. wide at base. Failed in 1916 from undermining due to faulty foundation, glacial drift.--(a); (b); E.N., Vol. 75, P. 1106.

(2) Failure Due to Faulty Means for Stream C Control During Construction

299. Dayton Dam, Ohio--High water ran over coffer dam and completed end of structure was undermined twice during construction.--E.R., Vol. 56, P. 414.

IX. FAILURE OF STEEL DAM

There was only one steel dam failed,due to inadequate cutoffs, which was called Hauser Lake Dam, Mont.

300. Hauser Lake Dam, Helena, Mont.--Built in 1906, 70 ft. high, 630 ft. long curved with steel plates resting on steel bents, and timber overflow apron. Upstream toe was protected with rubble masonry. Failed on Apr. 14, 1908, due to undermining of the foundation by leakage through or under the steel sheet pile cutoff.--(a); (b); E.N., Vol. 59, P. 491.

X. FAILURES OF TIMBER DAMS

Of 18 failures of timber dams, 2 were due to inadequate spillway; 5, due to inadequate cutoff wall or faulty foundation; 3, due to faulty construction and poor design; 2, due to inadequate means for stream control during construction; 2, due to improper operation and 5, due to miscellaneous causes.

(1) Failure Due to Inadequate Spillway

301. Middle Dam, Colo.--Built in 1894, 32 ft. high, 200 ft. long, 20 ft. wide at crest , with log crib filled with rock. Upstream slope was 1:1, faced with plank. Flashboards was 3 ft. high. Failed in

1909, due to overtopping.--(f), 15th Ed.

302. Clover Dam, Pa.--26 ft. high, failed in 1911, due to overtopping.--(a); (c)-1912.

(2) Failure Due to Inadequate Cutoffs & Faulty Foundation

303. Tacoma Light & Paper Co. Dam, Wash.--17 ft. high, 120 ft. long, built on yielding material. Failed in Dec. 1892, by undermining due to faulty foundation. --(b); E.N., Vol. 27, P. 112.

304. Kilbourn City Dam, Wis.--Built in 1895, 16 ft. high and 1,100 ft. long. Series of log cribs were filled with sand and stone. Failed in 1897, due to faulty foundation.--(a); E.N., Vol. 38, P. 161.

305. Dyer Dam, Danielsonville, Conn.--Built in 1879, 12 ft. high, and 208 ft. long. Crib work was filled with stone between massive masonry piers. Failed on March 18, 1901, due to faulty foundation under masonry bulkhead.--(a); E.N., Vol. 45, P. 231.

306. Mendota Dam, Calif.--Built in 1898, 16 ft. high, and 350 ft. long with 3 rows of sheeting apart 25 ft. and 20 in. into sandy soil tied together with 10 in.x 12 in. timber. Failed in 1916, due to undermining.--E.N., 1916.

307. Hamlin Lake Dam, Big Sable River, Mich.--Built in 1888. Failed in 1912, due to gradual under-

mining from leakage.--E.N., Vol. 68, PP. 361, 950.

(3) Failure Due to Faulty Cnstruction & Poor Design

308. Holyoke Dam, Mass.--It was swept away in 1848 shortly after first closing of gates, and before reservoir was full, because of poor construction.--E. N., Vol. 12, P. 190.

309. King's Mill Dam, Ingersoll, Ontario, Can. --Built about in 1848. Its earthen bank was constructed with timber crib overflow section, and failed in 1887, due to faulty construction and no repairs in 29 years after being built.--E.N., Vol. 17-18, P. 233.

310. Northfield Dam, Vt.--25 ft. high and 100 ft. long and 15 in. thick built on a radius of 50 ft. Failed on Aug. 27, 1890, due to poor design and construction and no engineering supervision.--(a); E.N., Vol. 47, P. 507.

(4) Failure Due to Inadequate Means for Stream Control during Construction

311. Montana Power Co. Dam, Butte, Mont.--60 ft. high and 500 ft. long, 100 ft. wide at base. Failed on Apr. 18, 1898. The freshet overflowed top during construction. Pressure and settlement caused vertical

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face to incline backward and rear timbers to incline forward.--E.R., Vol. 38, P. 203.

(5) Failure Due to Improper Operation

312. English Dam, Sierra Co., Calif.--Built in 1856, 100 ft. high, 331 ft. long, and 100 ft. wide at base. Crib was filled with rock faced with plank. Later it was backed with earth and rock, and flashboards added. Failed in June, 1883, due to decay of timber work.--(a); E.N., Vol. 22, P. 8; E.N.R., Vol. 100, P. 472.

313. Old Erie Canal Dam, Tonawanda, N. Y.--Built in 1824, of wooden dam flanked by masonry abutments. The wooden parts were renewed, masonry not. Failed on Jan, 7, 1916. Masonry pier between flood gated failed resulting the failure of the dam.--E.N., Vol. 75, PP. 94, 1121.

(6) Failure Due to Miscellaneous Causes

314. Arizona Canal,Dam, Phoenix, Ariz.--Built in 1887, 33 ft. high, 1000 ft. long, 36-48 ft. wide at base with timber crib filled with rock, fastened to bed rock, failed in 1905, due to break occurred with 7.7 ft. water on crest. 300 ft. of center section torn out.--E.N., Vol. 53, P. 450.

315. Lindauers Dam, Merrill, Wis.--It was built with timber crib filled with rock. Failed on July 24,

1912, when the water was then 15 ft. above normal.--E.N., Vol. 68, P. 233, 415, 541.

316. Eau Claire River Dam, Schofield, Wis.--8 ft. high, and 350 ft. long. Failed in 1912. Bank was washed away.--E.N., Vol. 68, PP. 233, 415, 541.

317. Iron River Dam, Ashland, Wis.--Failed in 1922.--E.N.R. VOL. 90, P. 380.

318. North Branch Dam, Freeman's Run, Austin, Pa. --Failed on July 18, 1942. E.N.R., Dec. 11, 1947.

XI. FAILURES OF DAMS UNCLASSIFIED & MISCELLANEOUS

(1). Failure Due to Inadequate Spillway

319. Honey Valley Land and Water Co. Dam, Long Valley Cr., Calif.--Failed in 1892, due to flood resulting from heavy rains.--E.N., Vol. 28, P. 529.

320. Clear Fork Dam, Trivity River, Fort Worth, Texas--Failed in 1894. The sudden rise of 15 ft. in river carrying away one wing of the dam.--E.R., Vol. 21, P. 200.

321. Lamont Dam, Pa.--Failure in 1903, during heavy rain and winds.--E.N., Vol. 49, P. 489.

(2) Failure Due to Inadequate Cutoff & Faulty Foundation

322. Ohio River Dam No. 26, Gallipolis, Ohio--Failed in 1912 by sliding on foundation resulting from 10.7 ft. head of water.--E.N., Vol. 66, PP. 177, and 206.

(3) Failure Due to Faulty Construction

323. Wausau Dam, Wisconsin River, Wis.--Concrete and masonry in front of old crib dam, failed on July 24, 1912. Failure occurred at junction of masonry and concrete.--E.N., Vol. 68, PP. 333, 415, 541.

(4) Failure Due to Faulty Design

324. Portersville Dam, Del.--Failed Apr. 4, 1903. High water carried out 40 ft. Design was inadequate.--E.N., Vol. 49, P. 313.

(5) Failure Due to Ice Pressure

325. Kinsman St. Res., Cleveland, Ohio--Failed in Dec. 1886, due to ice pressure and sudden drawing off of water.--E.N., Vol. 47, P. 507.

(6) Failure Due to Poor Foundation

326. Vernon Heights Res., Oakland, Cal.--Concrete and asphalt wall was built to increase capacity of reservoir. The wall was 8 ft. high, 2 ft. thick at base and 1 ft. at top. Failure on Oct. 20, 1896, due to shallow foundation, built partly on made foundation. --E.N., Vol. 47, P. 507.

(7) Failure Due to Miscellaneous Causes

327. Bancroft Dam, S. Peabody, Mass.--Failed on March 20, 1884.--E.N., Vol. 11, P. 153.

328-329. Beaver Brook Dams, Ansonia, Conn.--Two reservoir dams near Ansonia failed on March 26, 1884. --E.N., Vol. 10, P. 234; Vol. 11, P. 153.

330. New Port Water Works Dam, Lawton's Valley, Rhode Island--Failed on March, 26, 1884.--E.N., Vol. 11, P. 153.

331. Little Kanawha River Dam, Palestine, W. Va. --Failed in May 31, 1890.--E.N., Vol. 23, P. 313.

332. Alton Dam, Ontario, Can.--Failed on Nov. 13, 1889. Mill dam broke, causing 5 or 6 other dams below first to give way in turn.--E.B.R., Vol. 20, P. 362.

333. Price's Lake Dam, Carson, Nev.--Failure took place on July 6, 1890.--E.N., Vol. 24, P. 25.

334. Goldsboro Dam, Me.--Failed on May 16, 1890.

The failure caused several other dams and small bridges carried away by flood. The dam was considered unsafe for 2 years.--E.N., Vol. 23, P. 48.

335. Bonesteel Pond Dam, Troy, N. Y.--Failed on Sept. 18, 1890. Outlet gave way during flood.--E.N., Vol. 24, P. 25.

336. Lewiston Res., Huntsville, Ohio--Failed on May 3, 1893.--E.N., Vol. 29, P. 433.

337. Rage Mill Dam, Fergus Falls, Minn.--Failed on June 1, 1893.--(m).

338. State Dam, Hudson River, Troy, N. Y.--Failed on June 12, 1893.--E.N., Vol. 29, PP. 177, 553.

339. Knolbrook Dam, Jermyn, Pa.--Failed on Oct. 10, 1894.--E.N., V32, P. 309.

340. Gould Creek Dam, Cobden, Ontario, Can.--35 ft. high, 250 ft. long. Failed on Oct. 18, 1894.--E.N., Vol. 32, P. 333.

341. Hicksville Dam, Ohio--Failed in 1896 under the pressure of heavy rain.--E.R., Oct. 10, 1896, P. 342.

342. Brigham City Dam, Three-mile Creek, Utah--Failed on June 7, 1896,--E.R., June 27, 1896, P. 68.

343. Goodrich Creek Res. Buker City, Ore.--Failed on June 15, 1896.--E.N., Vol. 47, P. 507.

344-346. Ashland and Frackville Dams, Pa.--Three reservoir dams failed in 1901.--E.N., Vol. 46, P. 481.

347. Ashland Dam, N. H.--Built of stone. Failed on June 9, 1902, due to high water.--E.N., Vol. 47, P. 493.

348. Circleville Dam, Panquiteh Res., Utah--Built in 1903, and failed in 1903, under construction by wave action during heavy wind.--E.N., Vol. 49, P. 489.

349. Niobrara River Dam, Valentine, Nebr.--43 ft. high built of hollow shell with sand filling, slopes were 2:3 for upper stream, 3:2 for downstream. Failed in 1911 due to breakage of concrete over earth spillway and erosion of earth under neath.--E.R., Vol. 63, P. 459.

XII. CONCLUSIONS

From the foregoing investigation, we are led to the following conclusions:

1. Earth dams have more posibilities of failure than other types of dams. Most earth dam failures were caused by inadequate spillway, and by the steep slopes. The spillway of a dam should be of such a size adequately to care for not only the ordinary but the extraordinary floods; and the upstream slope should be such that under extraordinary flood will not do damage. Therefore, the importance of the hydrologic analysis and of the stability of slopes can never be over-

estimated.

2. Soil analysis pays an important role for any type of dam. Some dams failed only due to poor material taken from borrowpit. The cutoff walls must be an absolute stop to water flow or it muct so increase the path of percolation that the resistance to flow will be sufficient to prevent passage of any considerable quantity of water, with danger of saturation, piping, etc.

3. Foundation investigation and treatment are also two important factors of the stability of dams. The disastrous results of neglecting the geological structure of the foundation have been strikingly shown by many failures of dams.

4. So far as investigated, the arch dam is more stable than masonry dam of gravity type. It would be suggested that for important projects and good foundation, the arch dam would be considered first in selecting the type of structure, rather than any other type.

5. On the next pages there is a table summarizing the causes of 349 dam failures. It shows us a fact that almost one half of these investigated cases were the failures of the low dams, less than 50 ft. high. Hence, it would be emphasized here that the small dam needs the same careful attention as to foundation and design as does the large one.

TABLE I

Summation of 349 Dam Failures

Ref. No.	Cause of Dam Failures
1.	Inadequate spillway, overtopping by flood wave.
2.	Inadequate cutoffs. Porous foundation allowing leakage and erosion under earth dam, and/or sliding in rigid types.
3.	Faulty construction or material not property used.
4.	Faulty design; slopes too steep for earth dams; section too light for masonry dams.
5.	Inadequate means for stream control during construction.
6.	Excessive quantities of clay or other classes of fine material.
7.	Ice pressure or disintegration effect of.
8.	Burrowing rodents.
9.	Faulty foundation.
10.	Unstable or weak foundation.
11.	Insuffieient provision against erosion from back wash below dam or spillway.
12.	Earthquake.
13.	Wind action.
14.	Miscellaneous causes.
15.	Failure of bottom in a small water works reservoirs.
16.	Improper operation or inadequate maintenance.

Type	Height (feet)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	%
		Number in parentheses denote percentages of the total in each case; number of failures under each cause. Rerference number of cause refers to the list on last page.																	
Earth	0 - 50	43	24	4	4	4	3		2	1	1	2	1	1	2			92	(47)
	50 - 75	4	8	5	1		1		1	1		1		1	2			25	(13)
	75 - 100	1	3		1		2			1			1					9	(5)
	100 - 150		1	2		1	1			1	1			1				8	(4)
	150 -			1			2			2					1			6	(3)
	Not given	21	10	2			1	1		3				2	9	6		55	(28)
	Total %	69 (35)	46 (24)	14 (7)	6 (3)	5 (3)	10 (5)	1 (.5)	3 (2)	9 (4)	2 (1)	3 (2)	2 (1)	5 (3)	14 (6.5)	6 (3)		195 (100)	(100)
Rock-fill	0 - 50	2	1	1					1						1			6	(38)
	50 - 75			1														1	(6)
	75 - 100																		
	100 - 150	2	1	1			1											5	(31)
	Over 150	1		1														2	(13)
	Not given	1										1						2	(12)
	Total %	6 (38)	2 (13)	4 (25)			1 (6)		1 (6)			1 (6)			1 (6)			16 (100)	(100)
Arch	0 - 50			1				1										2	(22)
	50 - 100	1						1			2							4	(45)
	100 - 150			1							1							2	(22)
	Over 150				1													1	(11)
	Total %	1 (11)		2 (22)	1 (11)			2 (22)			3 (34)							9 (100)	(100)

Type	Height (feet)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	%
		Number in parentheses denote percentages of the total in each case; number of failures under each cause. Rerference number of cause refers to the list on P. 106.																	
Masonry Gravity	0 - 50	3	12	6	8										4		2	35	(50)
	50 - 75		2					5	1						2			10	(14)
	75 - 100		1															1	(1)
	100 - 150	3			1													4	(6)
	Over 150		1		1	1									1			4	(6)
	Not given	1	7	1		1		1				2			3			16	(23)
	Total %	7 (10)	23 (33)	7 (10)	10 (14)	2 (3)		6 (9)	1 (1)			2 (3)			10 (14)		2 (3)	70 (100)	(100)
Reinforced Concrete	0 - 50		6															6	(67)
	50 - 75		1															1	(11)
	Not given		1		1													2	(22)
	Total %		8 (89)		1 (11)													9 (100)	(100)
Steel	70		1															1	(100)
Timber	0 - 50	2	5	1	1										3			12	(61)
	75 - 75																1	1	(5)
	Not given			2											2		1	5	(34)
	Total %	2 (11)	5 (29)	3 (16)	1 (5)										5 (28)		2 (11)	18 (100)	(100)
Unclassified	Total %	3 (10)	1 (3)	1 (3)	1 (3)			1 (3)		1 (3)					23 (75)			31 (100)	
Grand Total %		88 (26)	86 (25)	31 (9)	19 (5)	8 (2)	11 (3)	10 (3)	5 (1)	10 (3)	5 (1)	6 (2)	2 (1)	5 (1)	53 (15)	6 (2)	4 (1)	349 (100)	

APPENDIXES

I. ALPHABETICAL LIST OF 349 DAM FAILURES

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